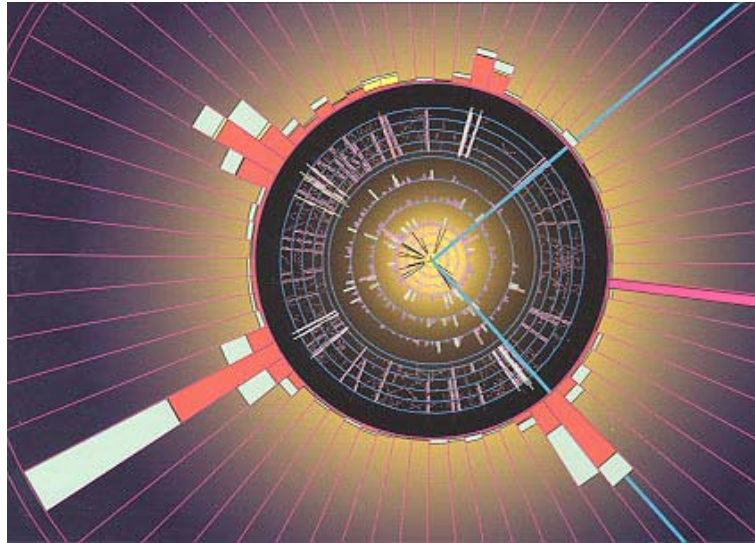




Physics at Hadron Colliders

Selected Topics: Lecture 2



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Dec. 30, 2002 – Jan. 11, 2003
Hue, Vietnam

http://d0server1.fnal.gov/users/klima/Vietnam/Hue/Lecture_2.pdf



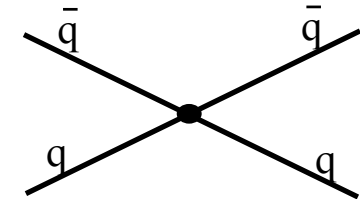
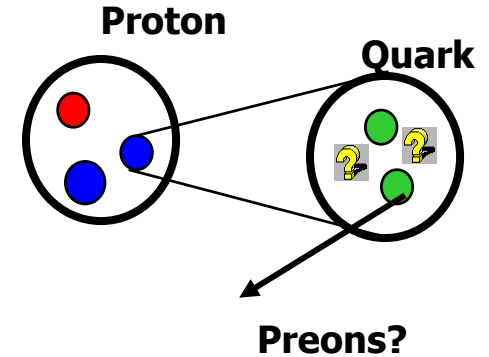
Jet Measurements (continued)



Using jets as a probe of quark structure

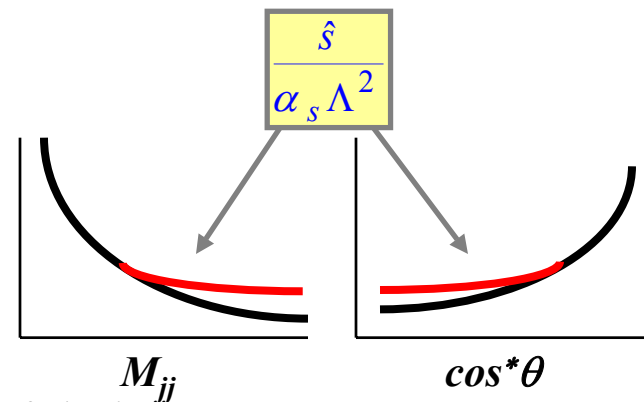


- If quarks contain smaller constituents
 - constituent interactions have a scale Λ
 - at momentum transfers $\ll \Lambda$, quarks appear pointlike and QCD is valid
 - as we approach scale Λ , interactions can be approximated by a four-fermion contact term:
 - at and above Λ , constituents interact directly



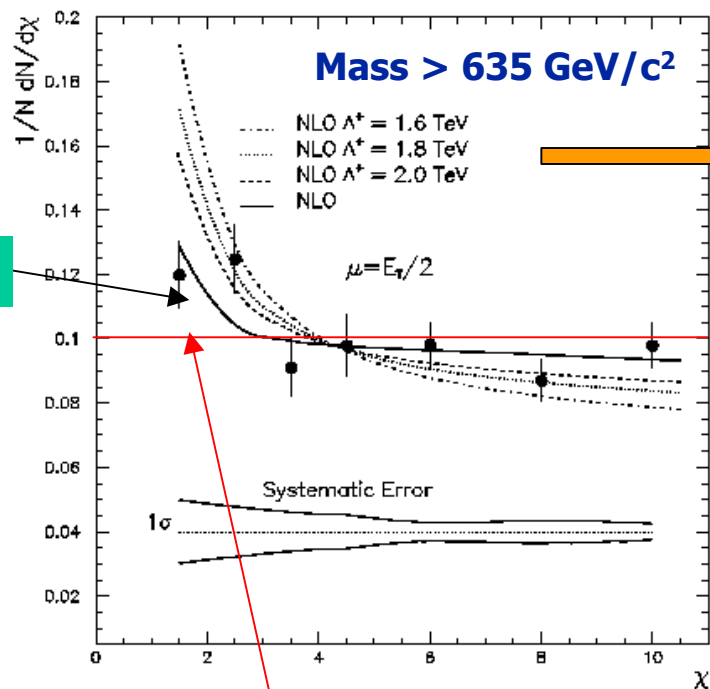
$$\sigma \sim [\text{QCD} + \text{Interference} + \text{Compositeness}]$$

Modifies dijet mass and centre of mass scattering angle distribution





DØ dijet angular distribution



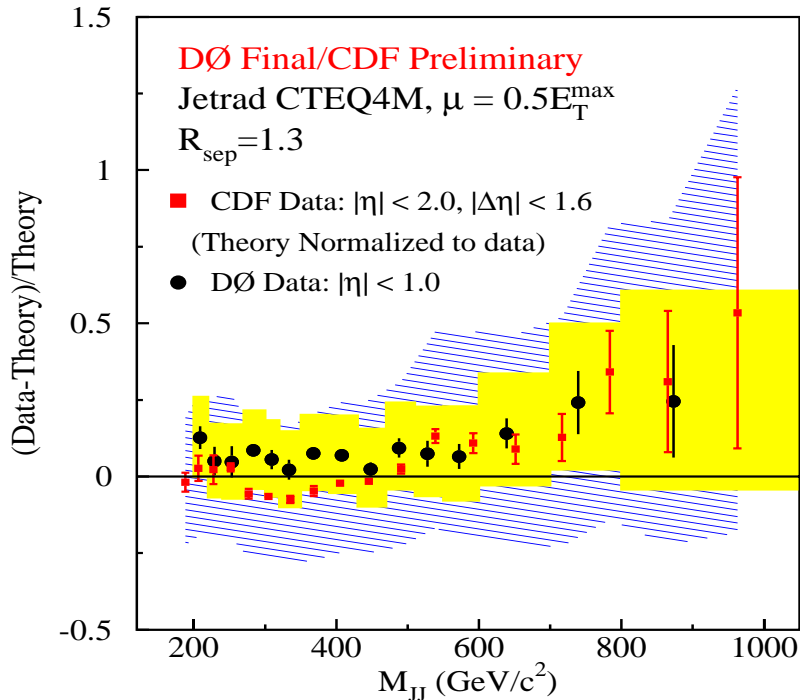
NLO QCD

Pure
Rutherford
scattering

95% CL Compositeness
Limit:
 $\Lambda^{(+,-)} \geq 2.1 - 2.4$ TeV

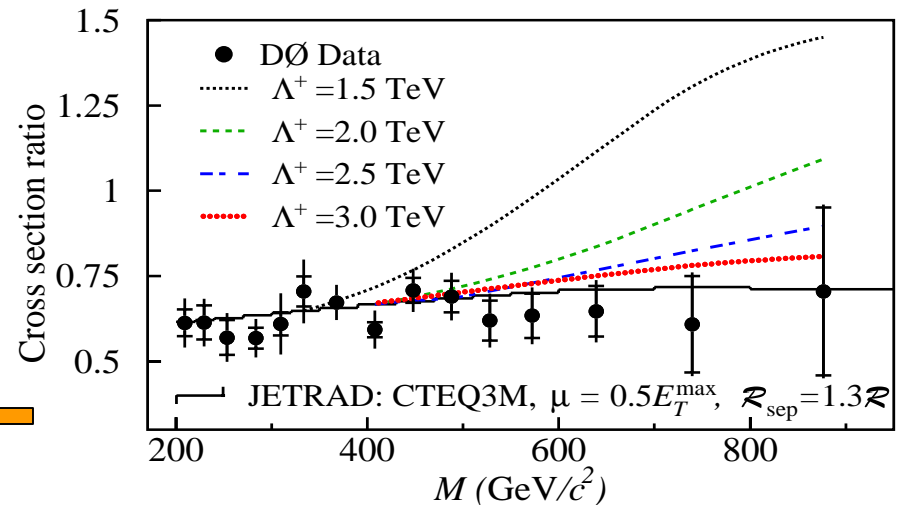


DØ and CDF dijet mass spectrum



Best limits come from combining mass and angular information: take ratio of mass distributions at central and forward rapidities (many systematics cancel):

$$\frac{dn / dM_{jj} (|\eta| < 0.5)}{dn / dM_{jj} (0.5 < |\eta| < 1.0)}$$



$\Lambda^+ > 2.7 \text{ TeV}$
 $\Lambda^- > 2.4 \text{ TeV}$



Jet cross sections at $\sqrt{s} = 630$ GeV

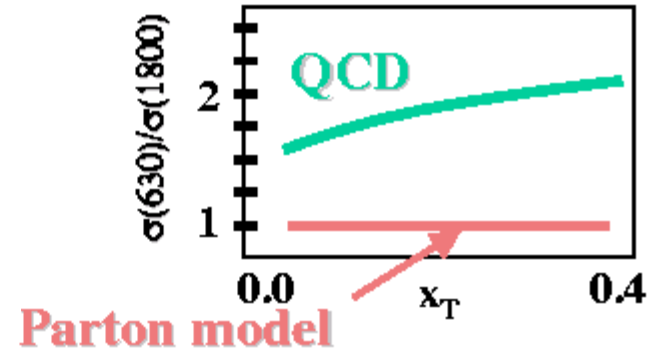
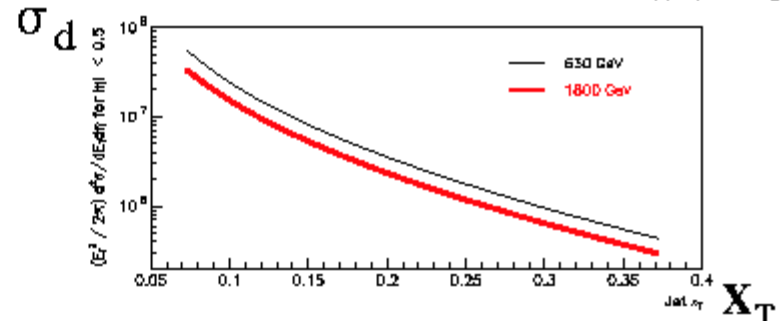
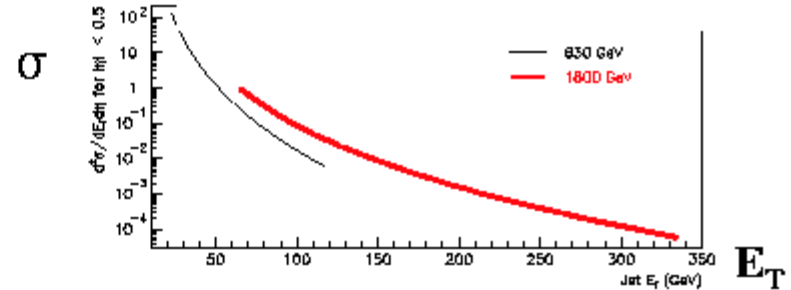
Ratio of the scale invariant cross section :

$$\sigma_d = (E_T^3 / 2\pi) (d^2\sigma / dE_T d\eta)$$

VS $X_T = E_T / (\sqrt{s} / 2)$

at different cm energies
(630 and 1800 GeV)

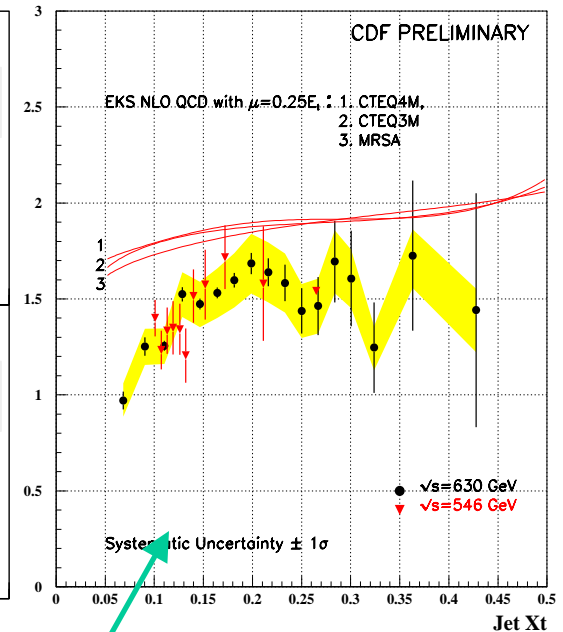
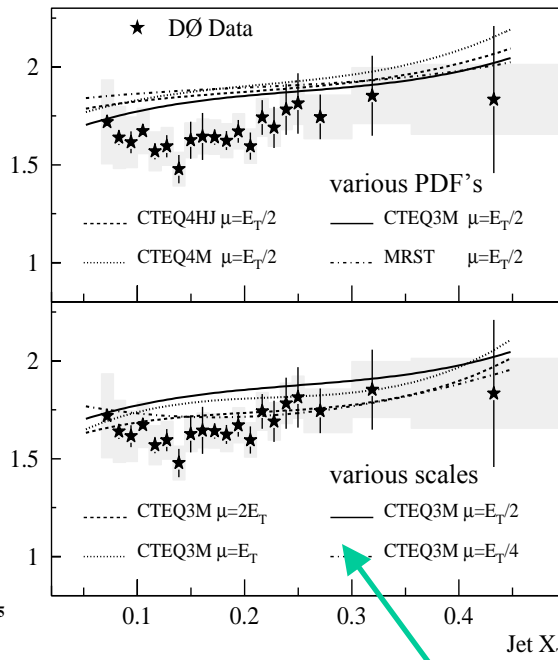
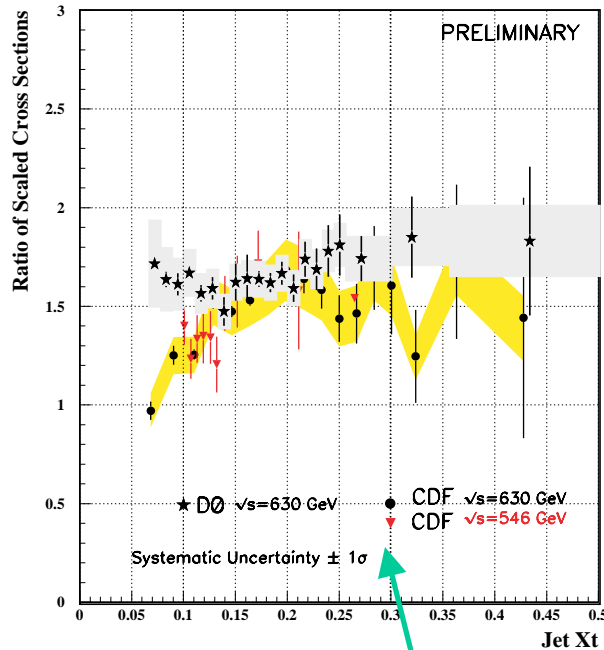
Ratio allows a substantial reduction in both theoretical and experimental systematic errors





Jet cross section ratio 630/1800 GeV

- **DØ and CDF both measure the ratio of scale invariant cross sections**
 $E_T^3 / 2\pi d^2\sigma / dE_T d\eta$ vs. $x_T = E_T / \sqrt{s}/2$ ($\equiv 1$ in pure parton model)



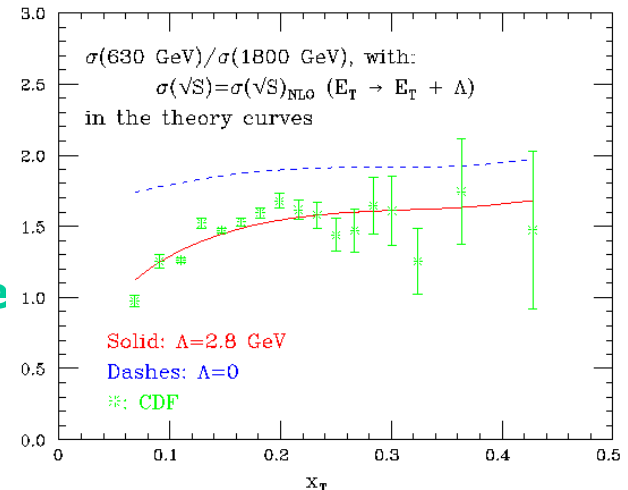
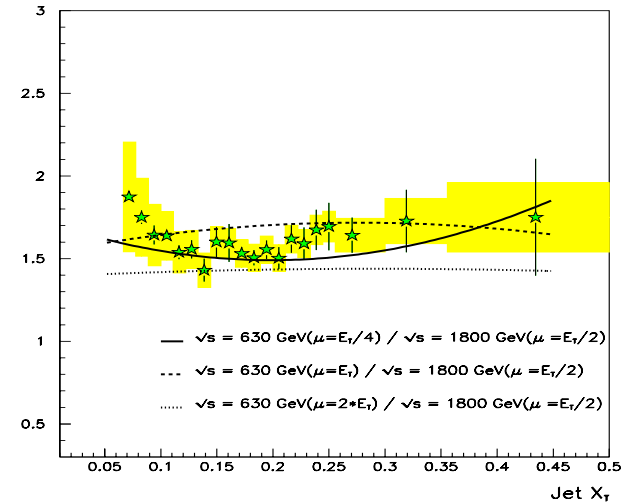
Not obviously consistent with each other (at low x_T) . . .

or with NLO QCD (at any x_T)



Suggested explanations

- Different renormalization scales at the two energies
 - OK, so it's allowed, but . . .
- Mangano proposes an $O(3 \text{ GeV})$ non-perturbative shift in jet energy
 - losses out of cone?
 - underlying event?
 - intrinsic k_T ?
 - could be under or overcorrecting the data (or even different between the experiments — DØ?)

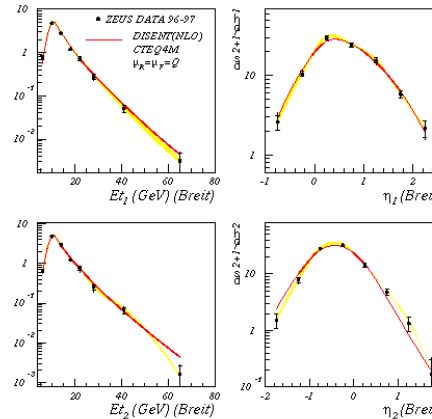
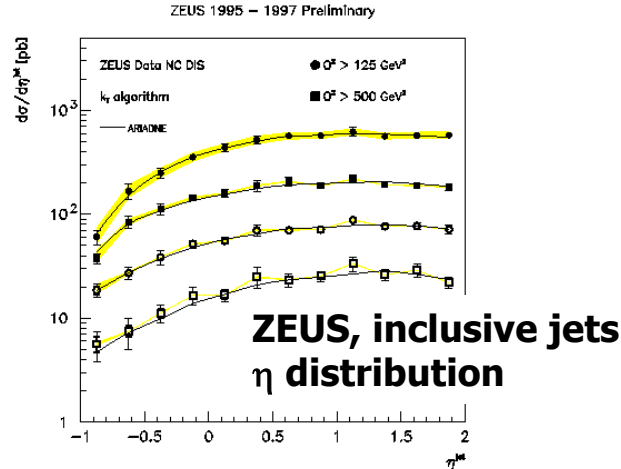
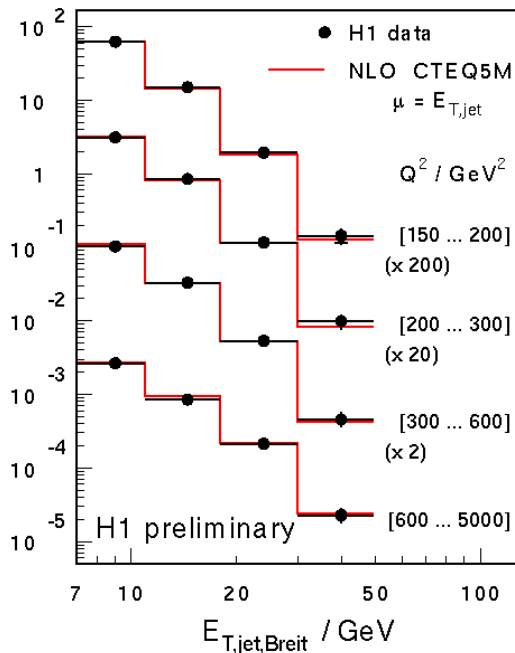




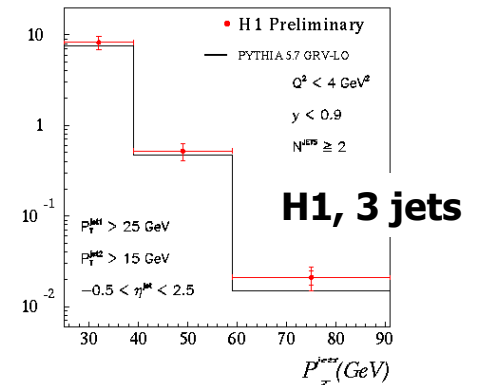
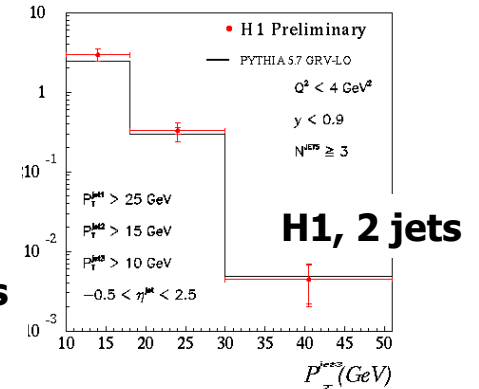
Jet production at HERA

- Inclusive jets, 2-jet and 3-jet cross sections at HERA - good agreement with QCD

H1, inclusive jets



ZEUS, 2 jets



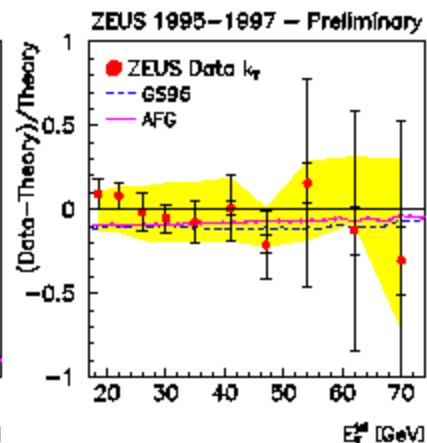
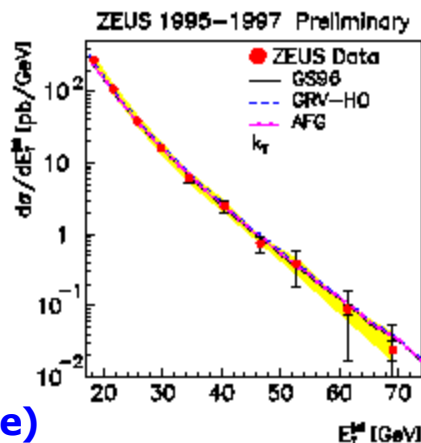


Jet production at HERA

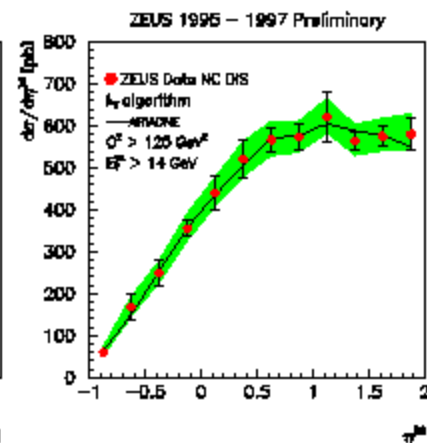
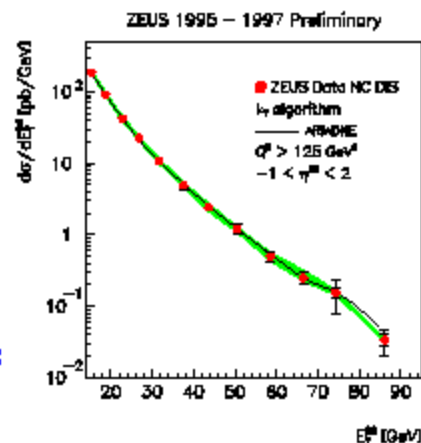
Photoproduction



(electron goes down the beampipe)

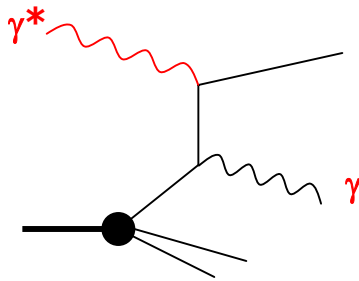


Deep Inelastic Scattering

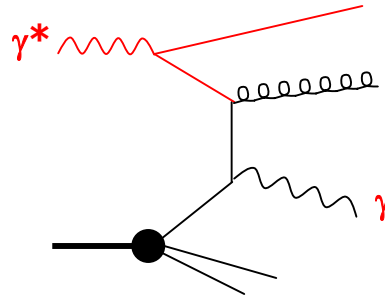




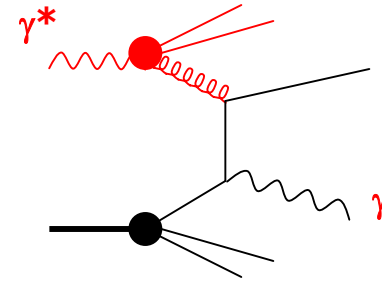
The photon structure function



Lowest-order process



Higher-order process



Photon structure function

Many of the higher order contributions to processes with incoming photons can be estimated by treating the photon as if it had hadronic structure.

This is called the photon structure function. It is really a resummation.

Useful because it is approximately independent of the rest of the process (just like the proton PDF) at least within a limited kinematic region (Q^2 small).

It is also the only PDF that is perturbatively calculable.



Jet cross sections: final remarks

- Jet measurements have started to become precision measurements
 - More data will settle the high- E_T issue CDF/DØ (if there is one)
- ... but this level of precision demands considerable care from the experimentalist, in understanding —
 - jet algorithms
 - jet calibrations
 - all the experimental errors and their correlations
 - the level of uncertainty in PDF's

Next topics:

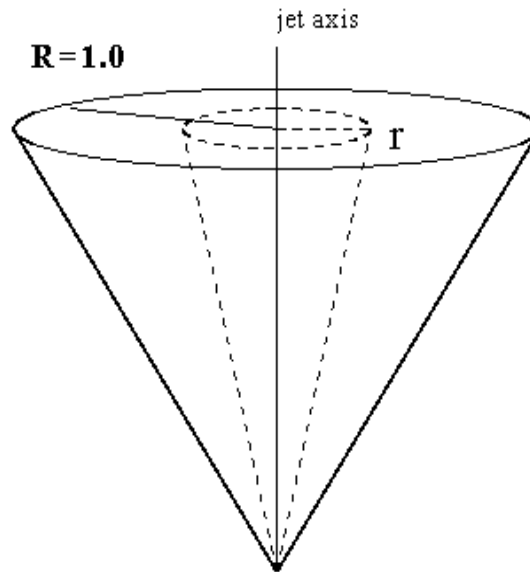
- jet characteristics and colour coherence
- QCD in the production of photons, W and Z, and heavy flavour
- measurements of α_s
- hard diffraction



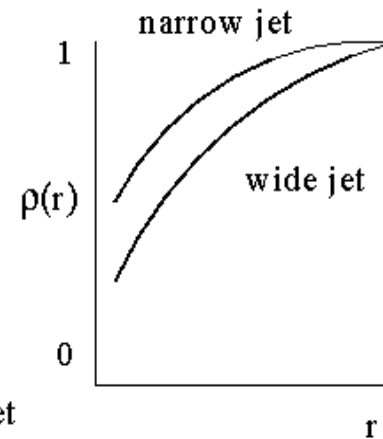
Jet Characteristics



Jet radial shape



Measure radial E_T
flow in 10 subcones
around jet axis in
 $\Delta r = 0.1$ increments



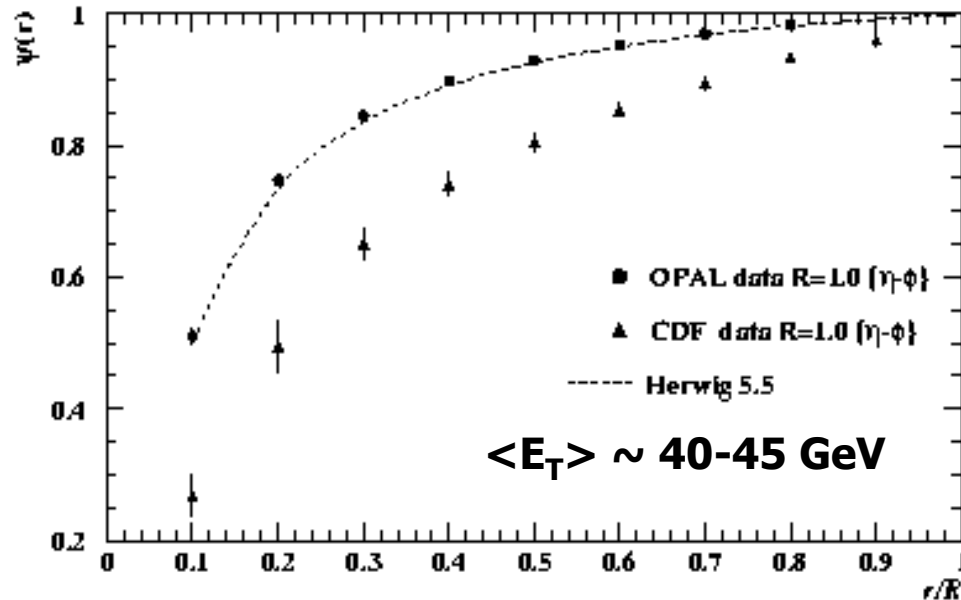
Calculate average integrated jet
 E_T fraction as a function of
radial distance from jet axis:

$$\rho(r) = 1/N_{\text{jets}} \left[\sum_{\text{jets}} (E_T(r)/E_T(R)) \right]$$



e^+e^- and $\bar{p}p$

OPAL and CDF, cone jets $R=1.0$

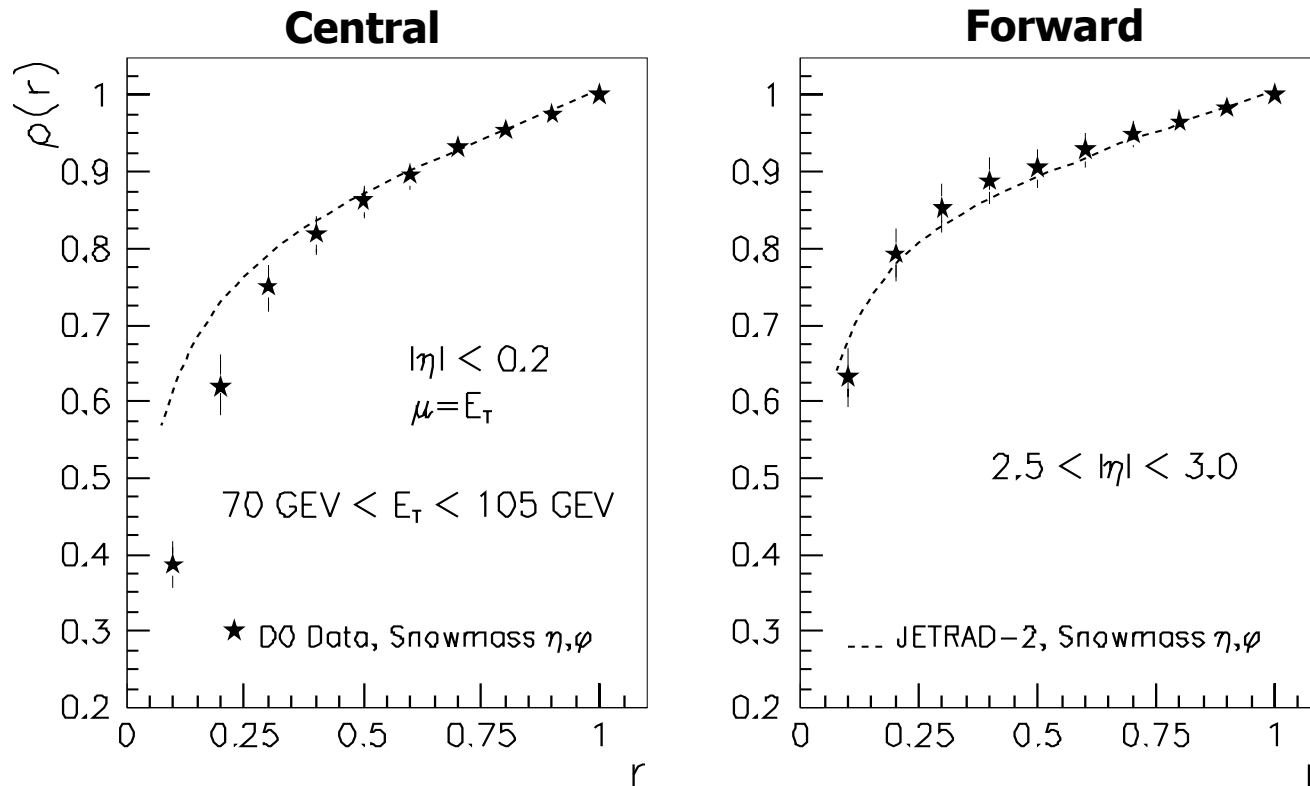


- Jets are broader in $\bar{p}p$ than e^+e^-
 - underlying event?
 - Corrected for, and should not be this large an effect
 - more gluons, fewer quarks?
 - simulation \rightarrow OPAL jets are $\sim 96\%$ quark jets, CDF jets are $\sim 75\%$ gluon-induced



DØ jet shape measurements

- Find forward jets are narrower than central jets: quark enriched?



- Also interesting that the JETRAD NLO calculation does pretty well at predicting the average shape, given that at most one gluon contributes



Quark jets and gluon jets

- Probability to radiate proportional to color factors:

$$\left| \text{q} \text{---} \text{g} \right|^2 \sim C_F = 4/3$$

$$\left| \text{g} \text{---} \text{g} \right|^2 \sim C_A = 3$$

- We might then naively expect

$$r \equiv \frac{\langle n_g \rangle}{\langle n_q \rangle} \equiv \frac{\langle \text{gluon jet multiplicity} \rangle}{\langle \text{quark jet multiplicity} \rangle} \sim \frac{C_A}{C_F} = \frac{9}{4}$$

- In fact higher order corrections and energy conservation reduce this:

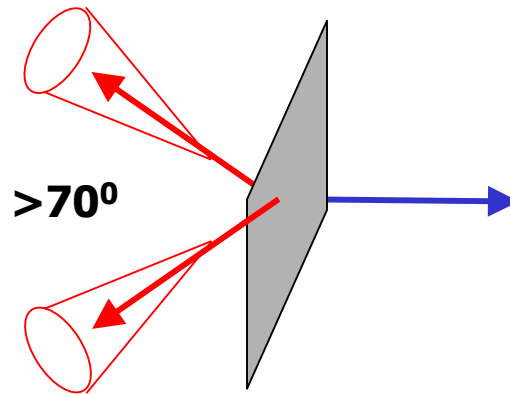
$$r = 1.5 \text{ to } 2.0$$



q and g jets at LEP

- Select identifiable samples by topology and b-tagging
 - e.g. OPAL inclusive q and g samples, LEP1

Two b-tagged jets



$>70^\circ$

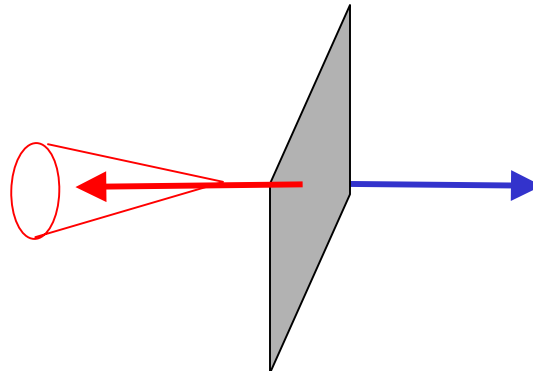
Plane \perp thrust axis

Treat hemisphere as a gluon jet

$E \sim 40$ GeV, purity $\sim 82\%$

~ 400 events

Two anti-b-tagged jets



Treat hemisphere as a u,d,s jet

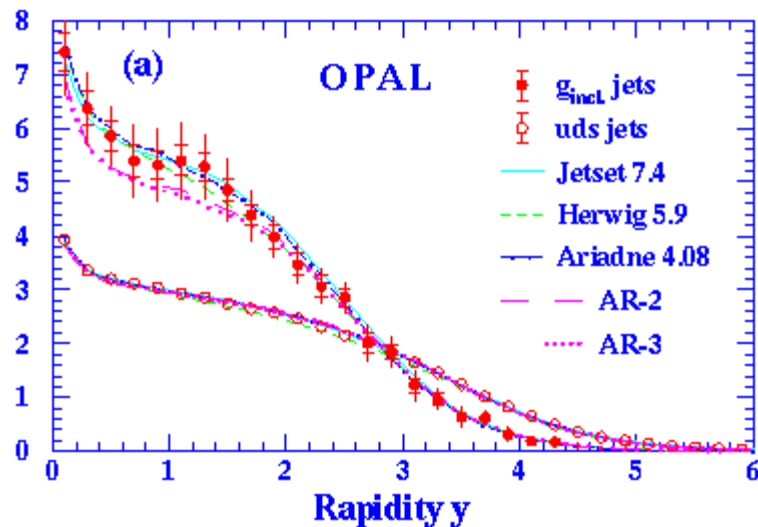
$E = 45.6$ GeV, purity $\sim 86\%$

$\sim 200,000$ events

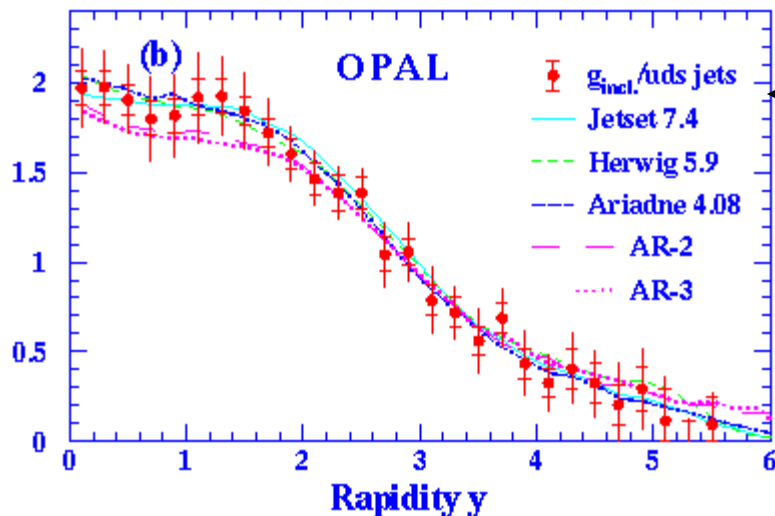


OPAL results

$$r = \frac{1}{N} \frac{dn^{\pm}}{dy}$$



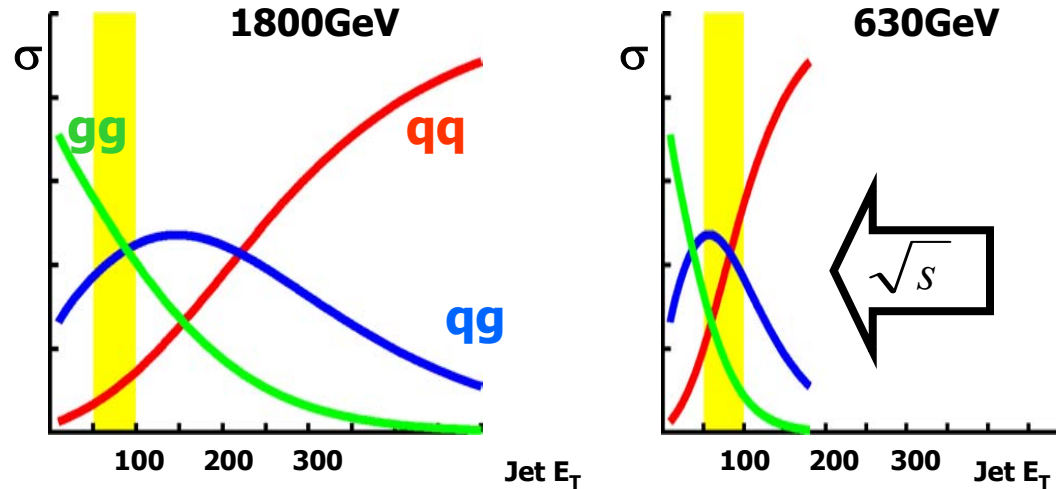
$$\frac{r(\text{gluons})}{r(\text{quarks})}$$



$R = 1.92$ for $|y| < 1$
cf. C_A/C_F



Separating q and g jets



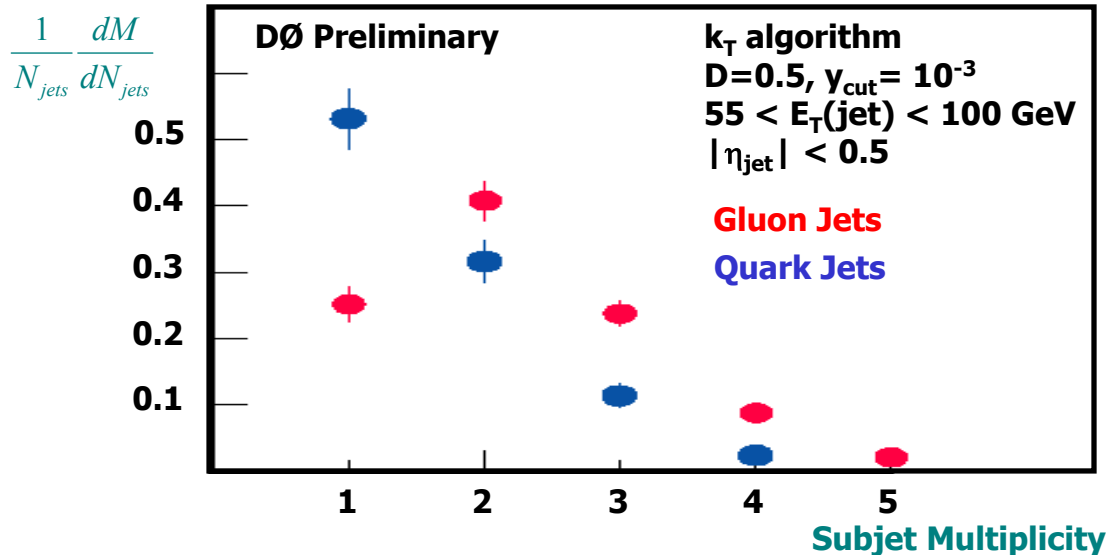
- Contributions of different initial states to the cross section for fixed jet E_T vary with \sqrt{s}
 - simulation: gluon fraction = 33% at 630 GeV, 59% at 1800 GeV
- Unravel jets until all subjects are separated by $y = 0.001$
- Compare jets of same (E_T, η) produced at different \sqrt{s}
 - assume relative q/g content is as given by MC and quark/gluon jet multiplicities do not depend on \sqrt{s}



Quark and Gluon Jet Structure

- measure $M^{630} = f_g^{630} M_g + (1 - f_g^{630}) M_q$
 $M^{1800} = f_g^{1800} M_g + (1 - f_g^{1800}) M_q$

Dominant uncertainties come from g jet fraction and jet E_T scale



DØ Data

$$R = \frac{\langle M_g \rangle - 1}{\langle M_q \rangle - 1} = 1.91 \pm 0.04$$

HERWIG 5.9

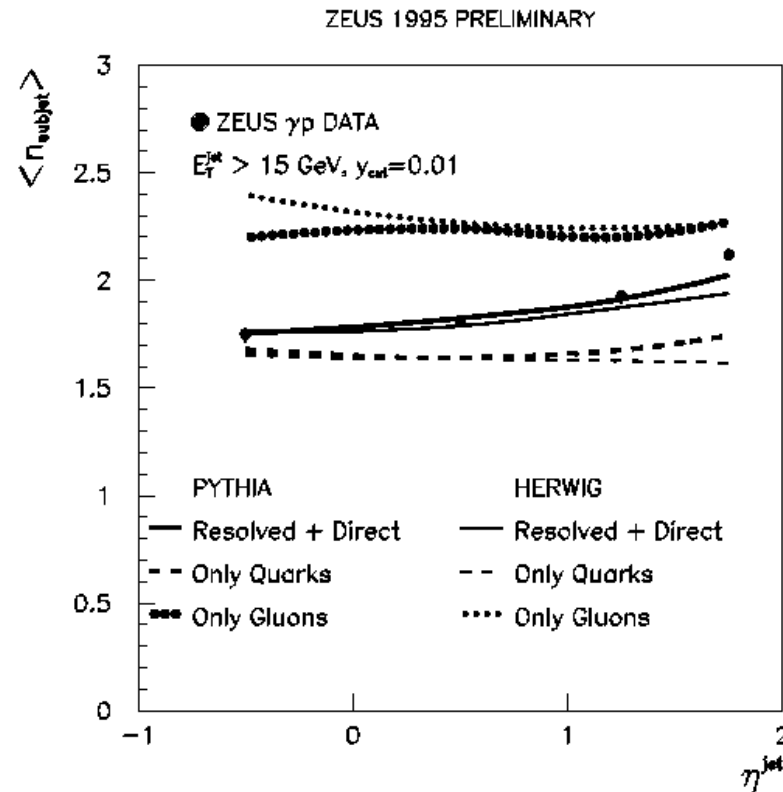
$$R = 1.86 \pm 0.04$$

- Have we glimpsed the holy grail (quark/gluon jet separation)?
 - The real test will be to use subjet multiplicity in (for example) the top \rightarrow all jets analysis, but unfortunately this will probably have to wait for Run II (DØ has done a little in its Run I publication)



Jet structure at HERA

- ZEUS: subjet multiplicity rises as jets become more forward
- Consistent with expectations (more gluons) and HERWIG

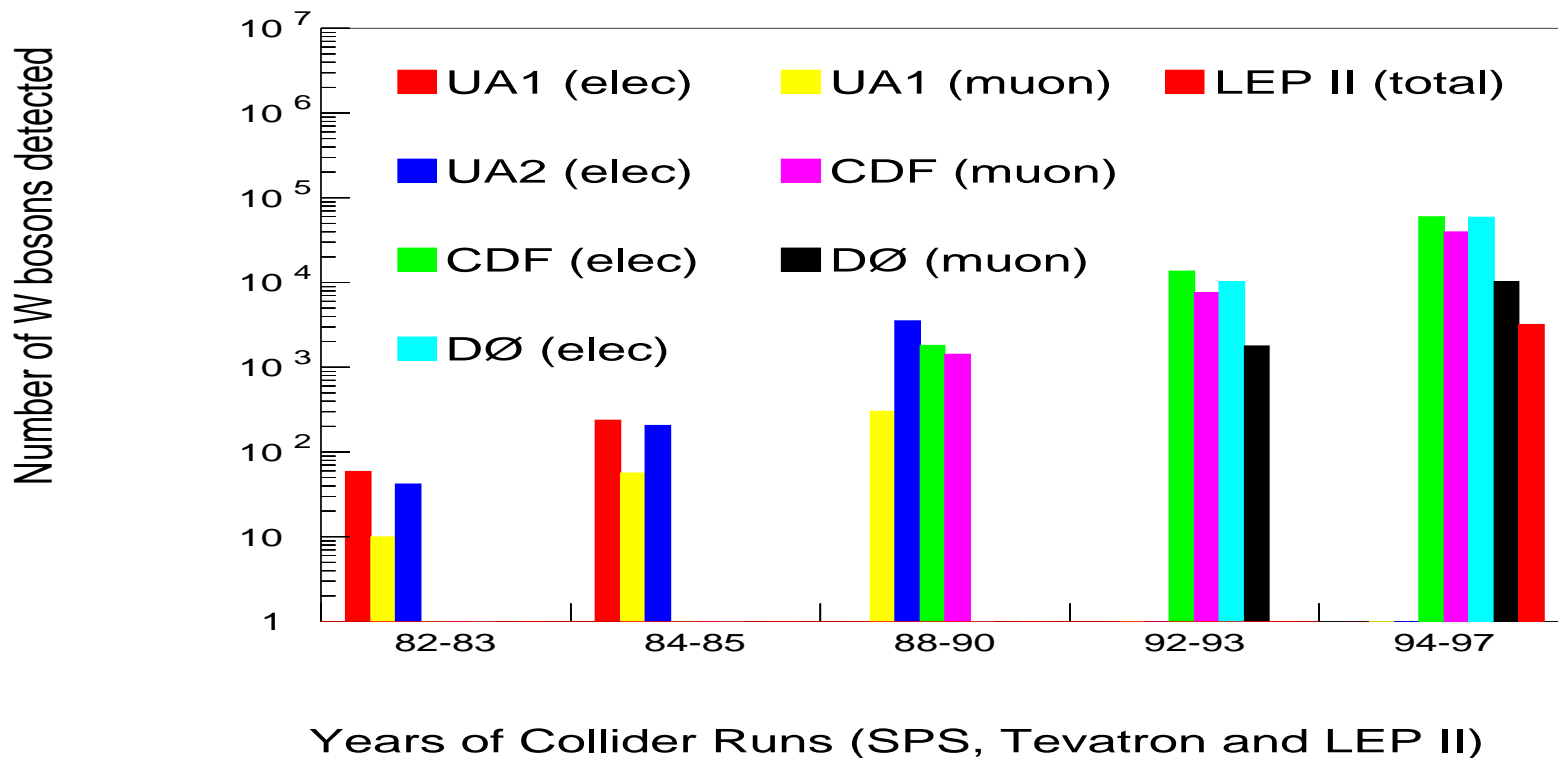




Weak Bosons



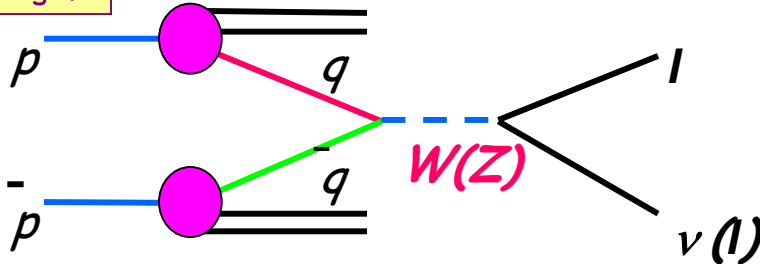
W samples





W and Z production at hadron colliders

$O(\alpha_s^0)$

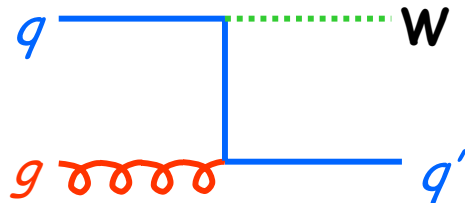


Production dominated by $q\bar{q}$ annihilation
(~60% valence-sea, ~20% sea-sea)

Due to very large $pp \rightarrow jj$ production, need to use leptonic decays

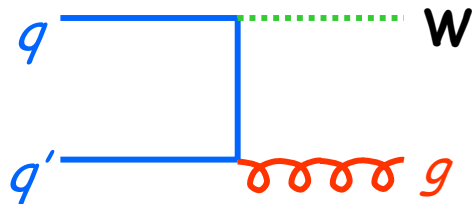
BR ~ 11% (W), ~3% (Z) per mode

$O(\alpha_s)$



Higher order QCD corrections:

- Boson produced with mean $p_T \sim 10$ GeV
- Boson + jet events ($W+\text{jet} \sim 7\%$, $E_T^{\text{jet}} > 25$ GeV)
- Inclusive cross sections larger
- Boson decay angular distribution modified



Benefits of studying QCD with W&Z Bosons:

- Distinctive event signatures
- Low backgrounds
- Large Q^2 ($Q^2 \sim \text{Mass}^2 \sim 6500 \text{ GeV}^2$)
- Well understood Electroweak Vertex





W and Z p_T

- **Large p_T (> 30 GeV)**
 - use pQCD, $O(\alpha_s^2)$ calculations exist
- **Small p_T (< 10 GeV)**
 - resum large logarithms of M_W^2/p_T^2

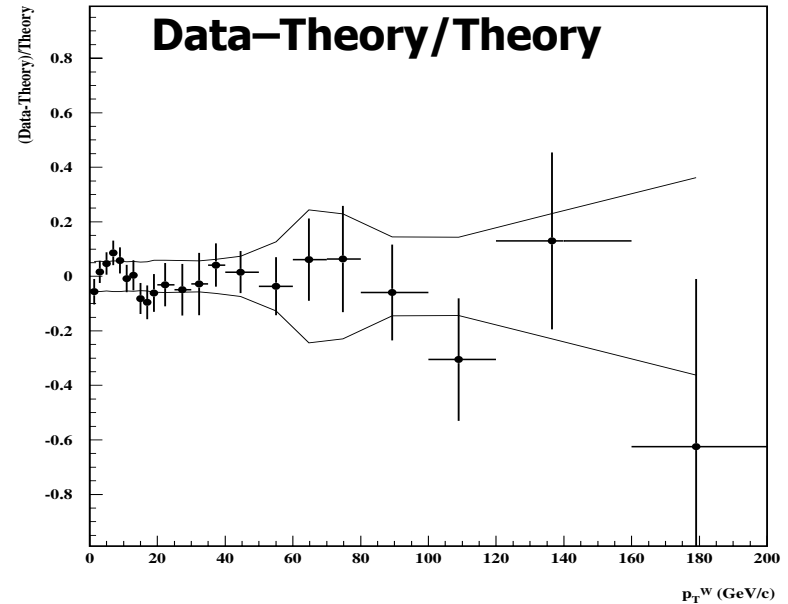
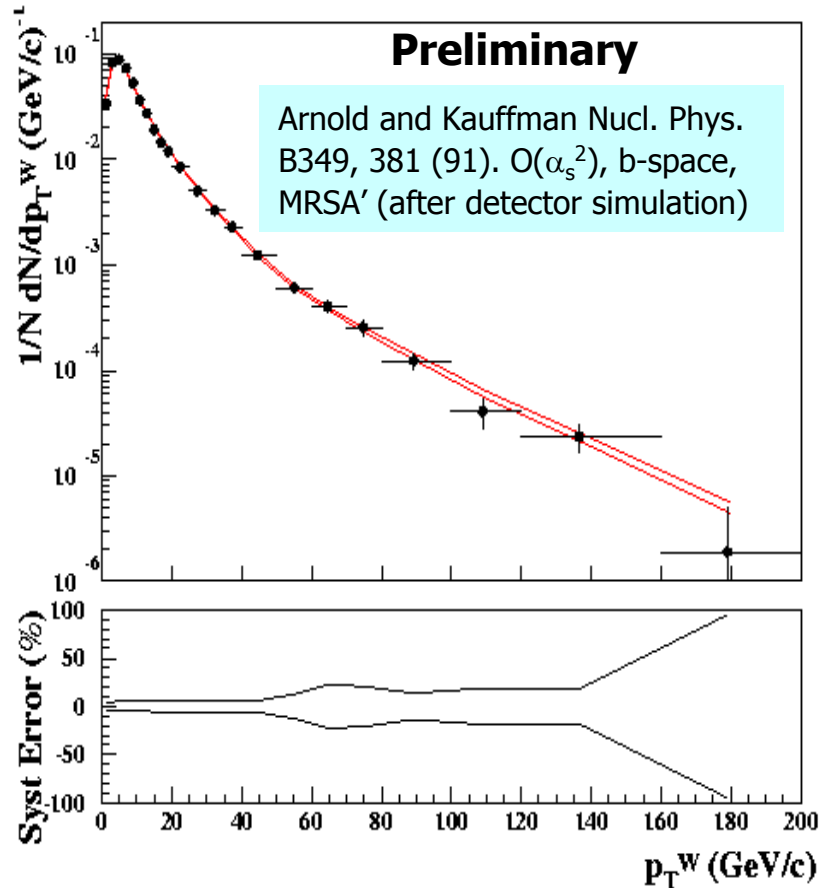
$$\frac{d\sigma}{dp_T^2} \sim \frac{\alpha_s}{p_T^2} \ln\left(\frac{M_W^2}{p_T^2}\right) \left[v_1 + v_2 \alpha_s \ln^2\left(\frac{M_W^2}{p_T^2}\right) \right]$$

- **Match the two regions and include non-perturbative parameters extracted from data to describe $p_T \sim \Lambda_{\text{QCD}}$**

DØ p_T^W measurement



Preliminary



$$\chi^2/\text{dof}=7/19 \quad (p_T^W < 120 \text{ GeV}/c)$$

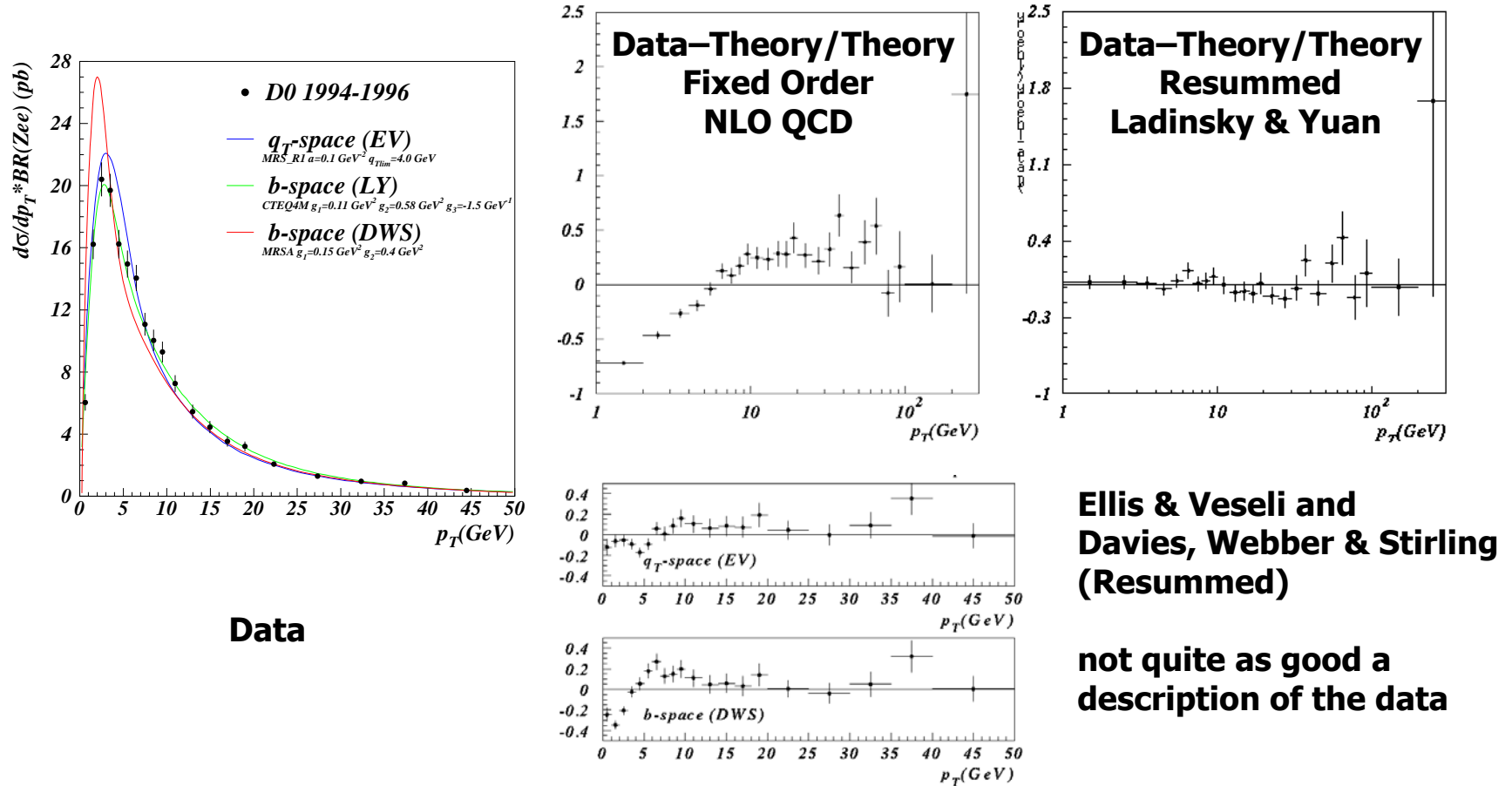
$$\chi^2/\text{dof}=10/21 \quad (p_T^W < 200 \text{ GeV}/c)$$

- Resolution effects dominate at low p_T
- High p_T dominated by statistics and backgrounds



DØ p_T^Z measurement

- New DØ results hep-ex/9907009



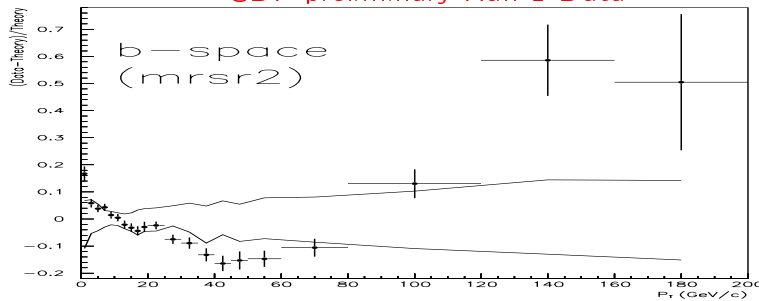


CDF p_T^W and p_T^Z

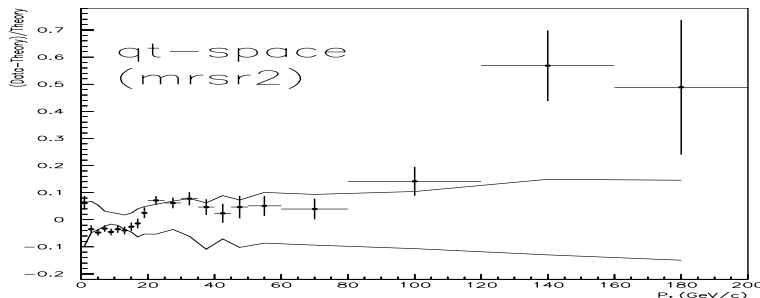
Ellis, Ross, Veseli, NP B503, 309 (97). $O(\alpha_s)$, q_T space, after detector simulation.

$$\frac{(Data - Theory)}{Theory}$$

CDF preliminary Run 1 Data

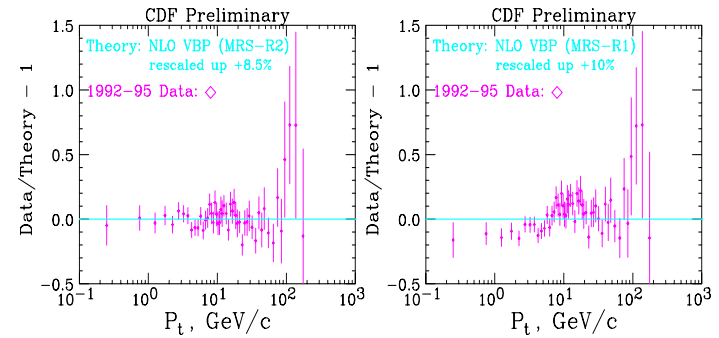
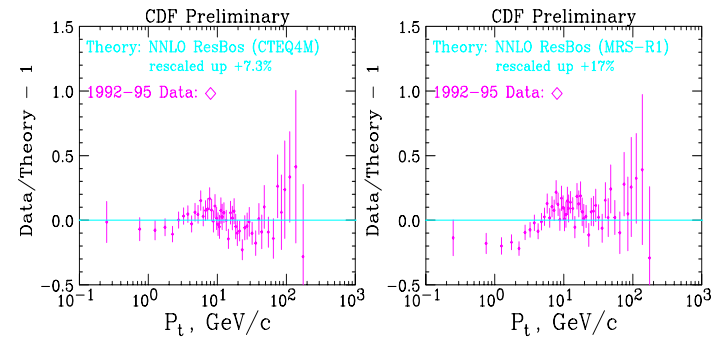


$\chi^2/d.o.f. = 1.85$ ($P_T^W < 120$ GeV/c), 2.49 (< 200 GeV/c)



$\chi^2/d.o.f. = 1.05$ ($P_T^W < 120$ GeV/c), 1.71 (< 200 GeV/c)

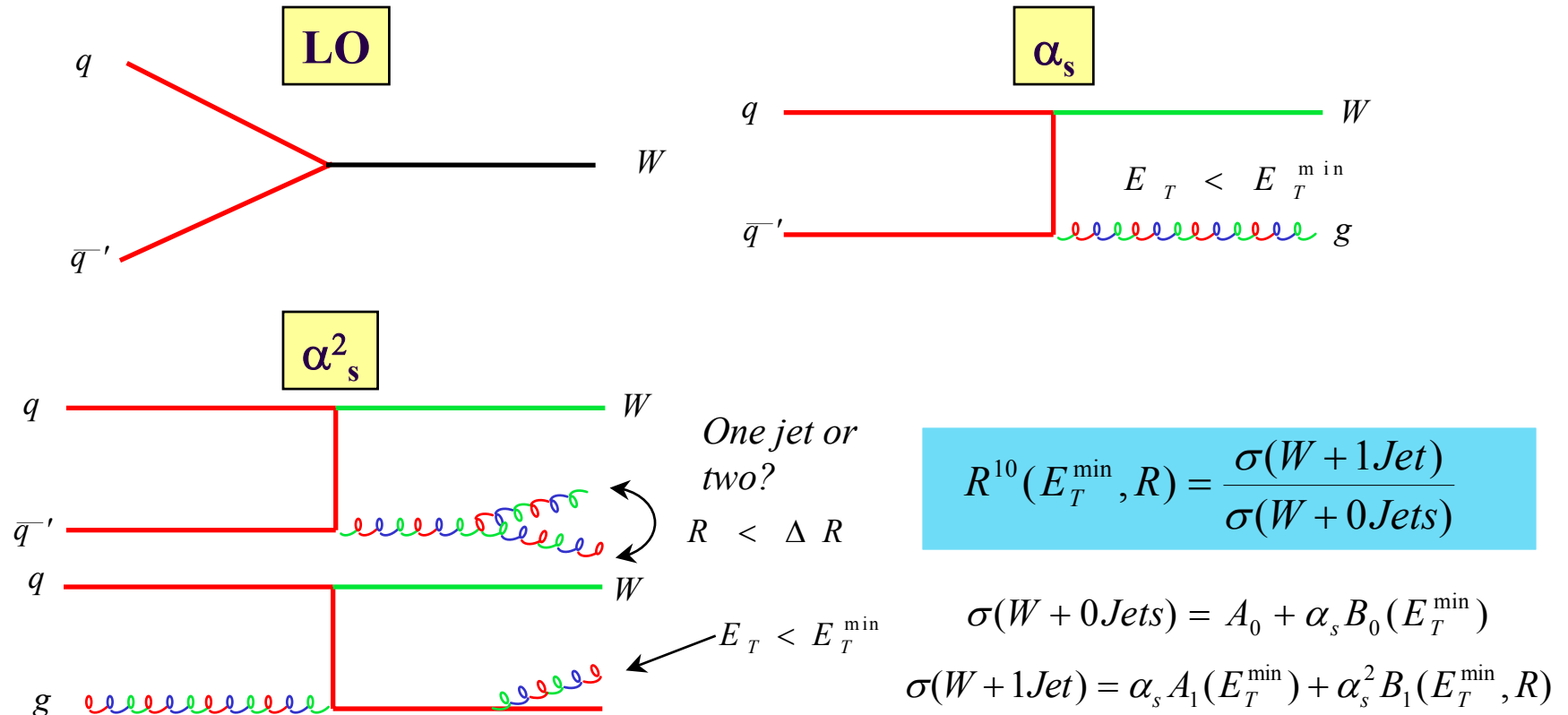
ResBos: Balasz, Yuan, PRD 56, 5558 (1997), $O(\alpha_s^2)$, b-space
VBP: Ellis, Veseli, NP B511,649 (1998), $O(\alpha_s)$, q_T -space





W + jet production

- A test of higher order corrections:

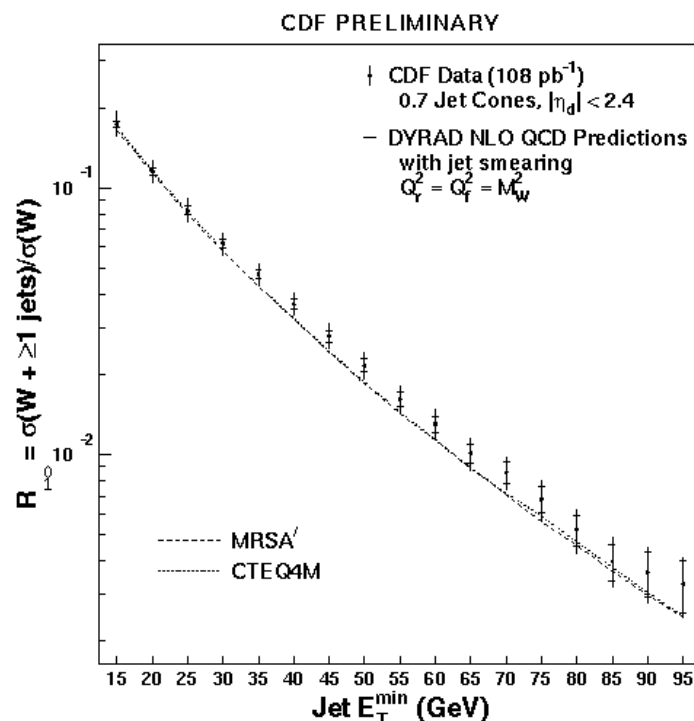
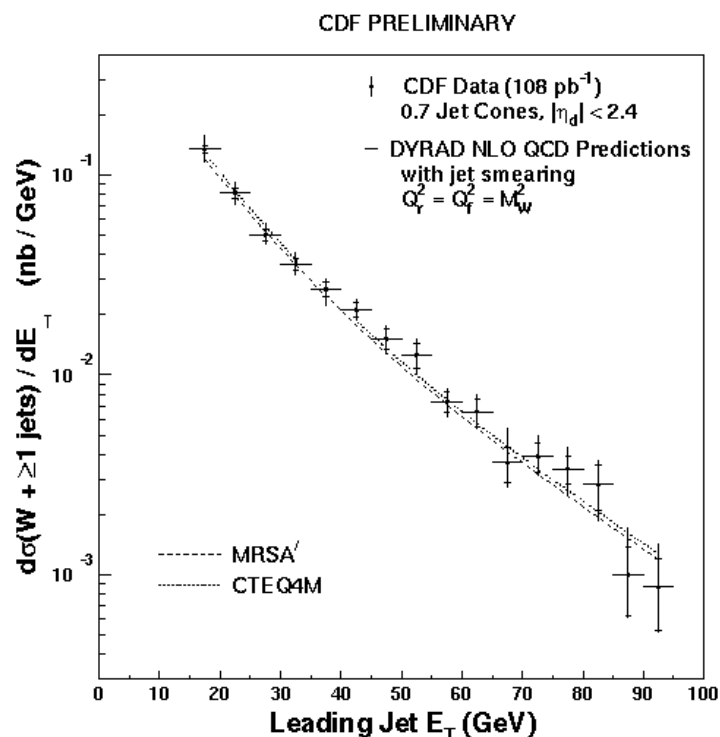


- Calculations from DYRAD (Giele, Glover, Kosower)



W + jet measurements

- DØ used to show a W+1jet/W+0jet ratio badly in disagreement with QCD. This is no longer shown (the data were basically correct, but there was a bug in the DØ version of the DYRAD theory program).
- CDF measurement of W+jets cross section agrees well with QCD:



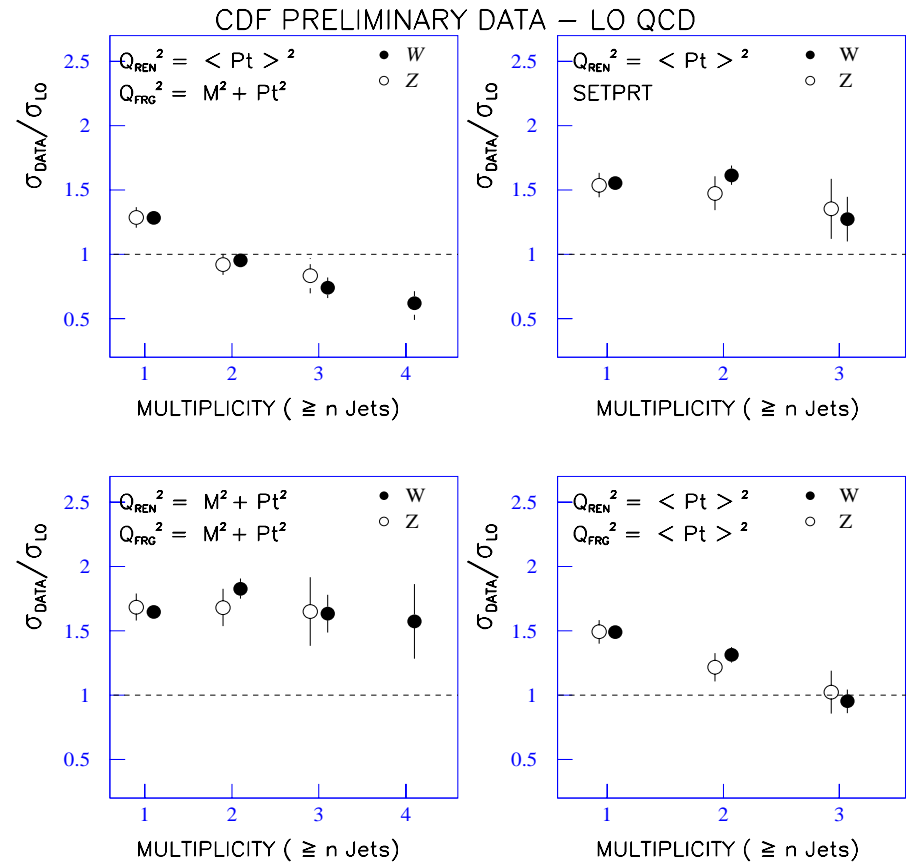
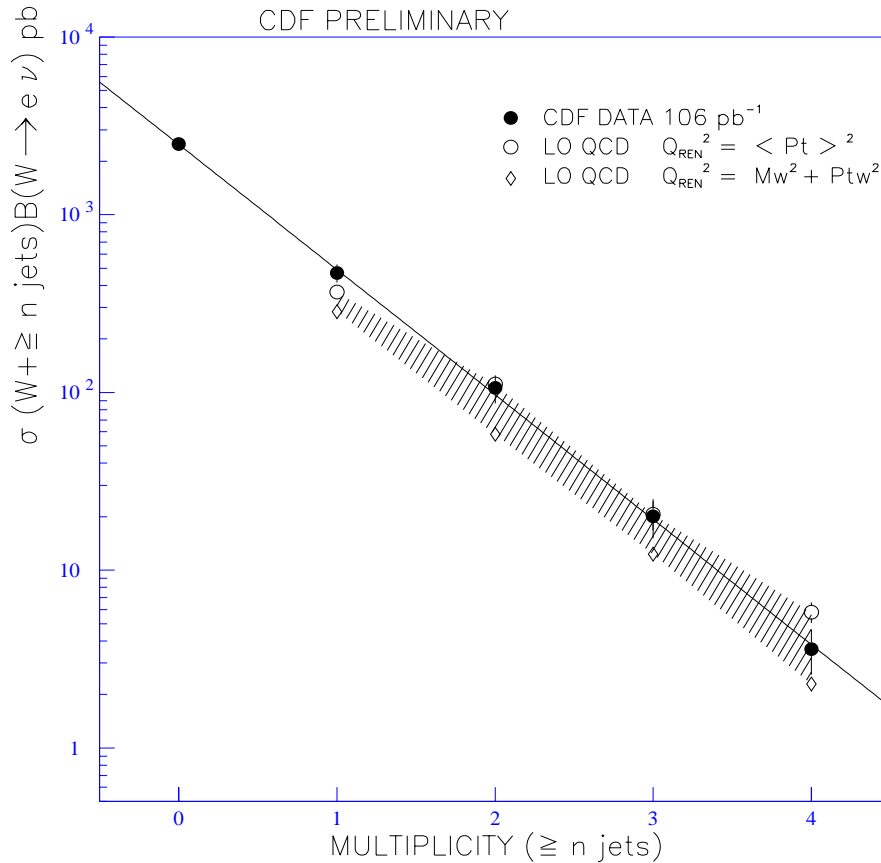


CDF W/Z + n jets



19/03/96 09.34

20/03/96 14.25

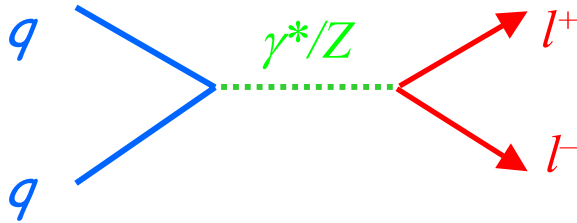


- Data vs. tree-level predictions for various scale choices
- These processes are of interest as the background to Top, Higgs, etc.

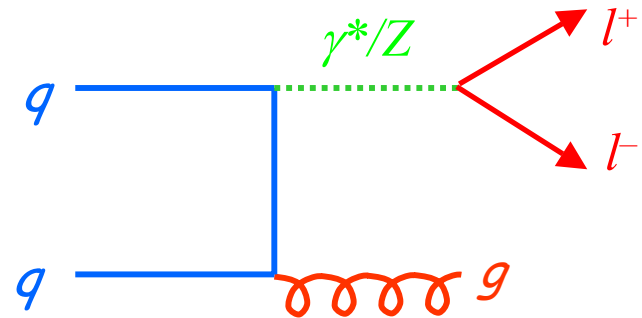
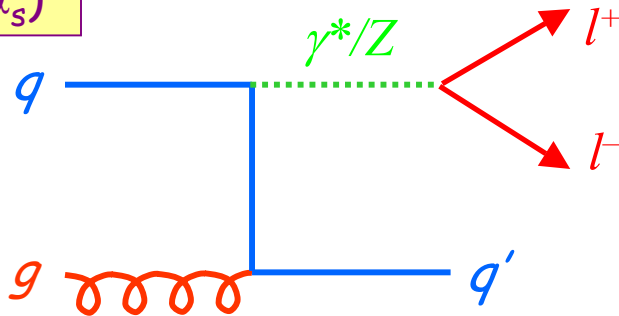


Drell-Yan process

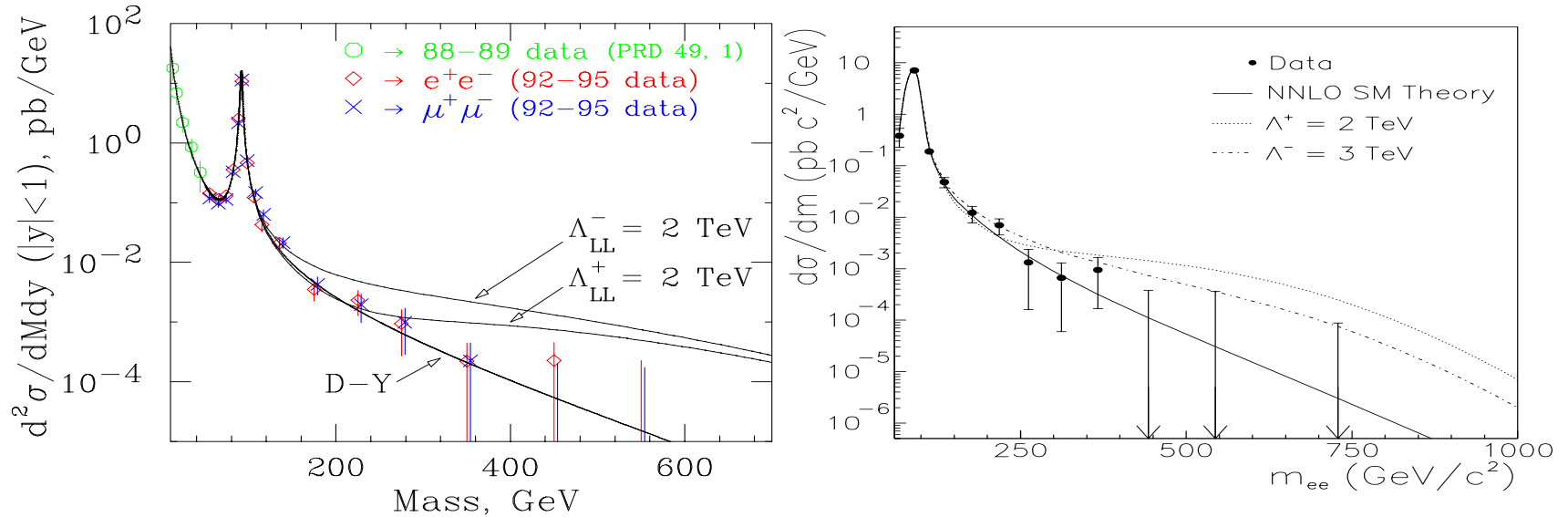
$O(\alpha_s^0)$



$O(\alpha_s)$



- Measure $d\sigma/d_M$ for $\bar{p}p \rightarrow l^+l^- + X$
- Because leptons can be measured well, and the process is well understood, this is a sensitive test for new physics (Z' , compositeness)



- **Compositeness limits: 3 – 6 TeV**
Assuming quarks & leptons share common constituents
(Limits depend on assumed form of coupling)

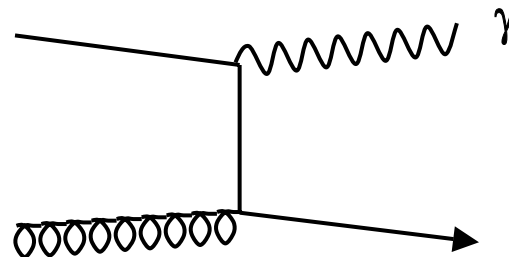


Photons



Motivation for photon measurements

- For the last 20 years or so, direct photon measurements have been claimed to:
 - Avoid all the systematics associated with jet identification and measurement
 - photons are simple, well measured EM objects
 - emerge directly from the hard scattering without fragmentation
 - Hoped-for sensitivity to the gluon content of the nucleon
 - “QCD Compton process”



- In fact, as we shall see, these promises remain largely unfulfilled, but we have still learned a lot along the way

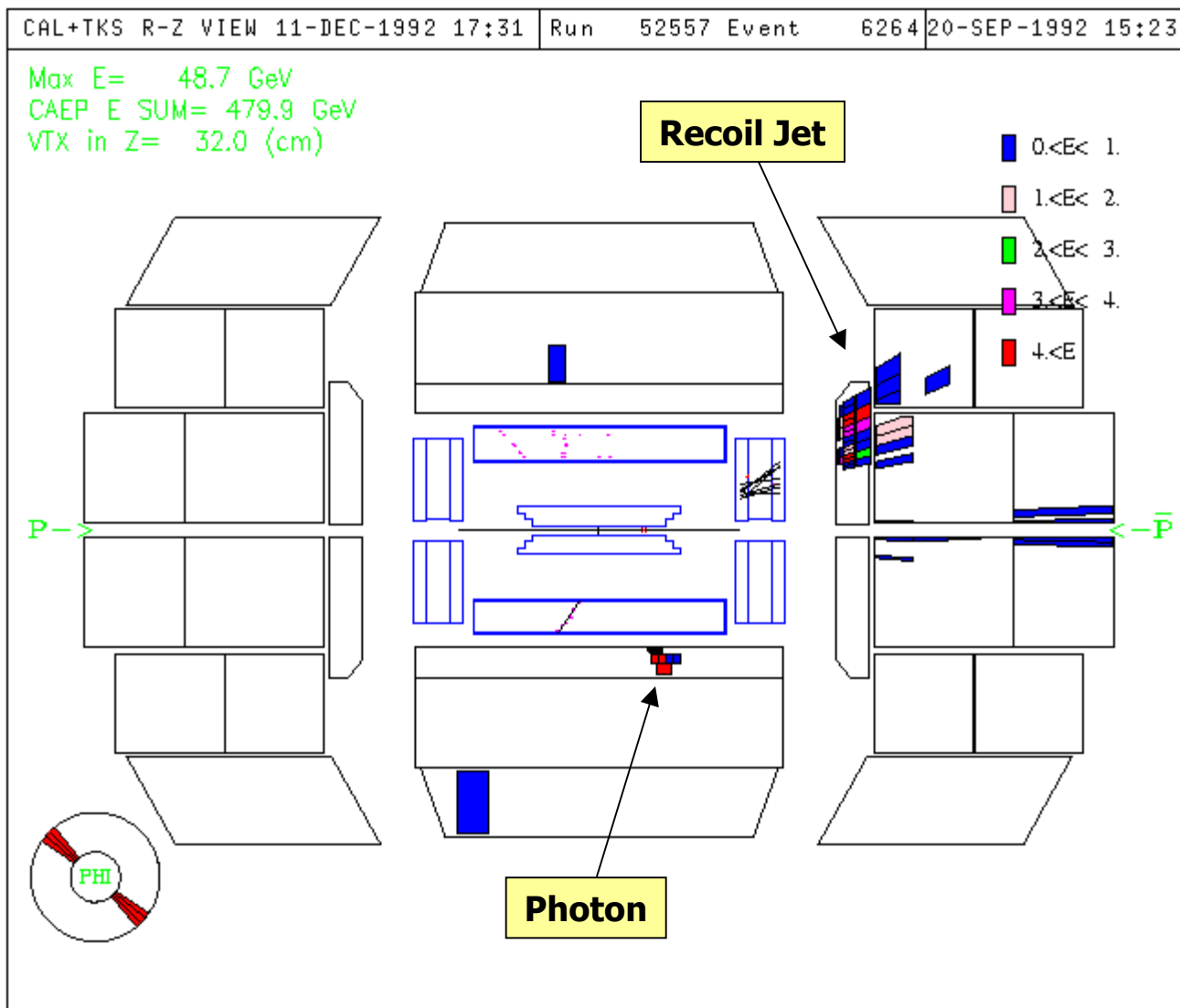


Photon identification

- Essentially every jet contains one or more π^0 mesons which decay to photons
 - therefore the truly inclusive photon cross section would be huge
 - we are really interested in direct (prompt) photons (from the hard scattering)
 - but what we usually have to settle for is isolated photons (a reasonable approximation)
 - isolation: require less than e.g. 2 GeV within e.g. $\Delta R = 0.4$ cone
- This rejects most of the jet background, but leaves those (very rare) cases where a single π^0 or η meson carries most of the jet's energy
- This happens perhaps 10^{-3} of the time, but since the jet cross section is 10^3 times larger than the isolated photon cross section, we are still left with a signal to background of order 1:1.



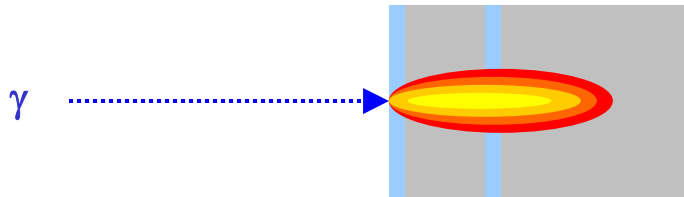
Photon candidate event in DØ



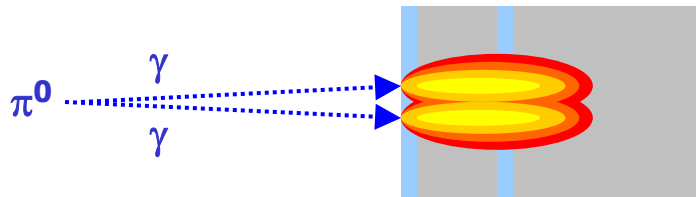


Signal and Background

- Photon candidates: isolated electromagnetic showers in the calorimeter, with no charged tracks pointed at them
 - what fraction of these are true photons?
- Signal



- Background



**Preshower
detector**

**Shower maximum
detector**

Experimental techniques

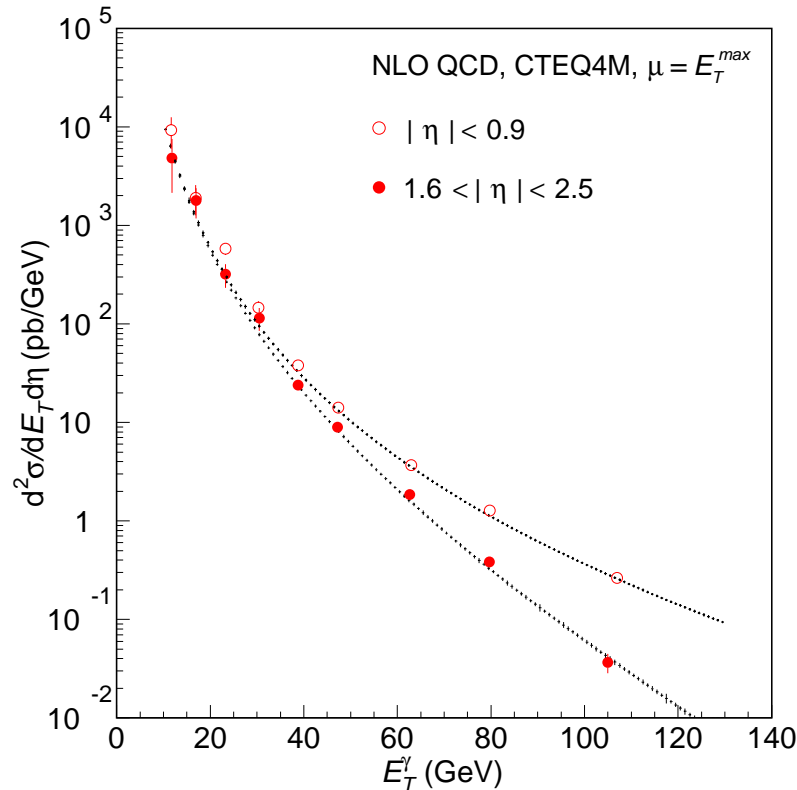
- DØ measures longitudinal shower development at start of shower
- CDF measures transverse profile at start of shower (preshower detector) and at shower maximum



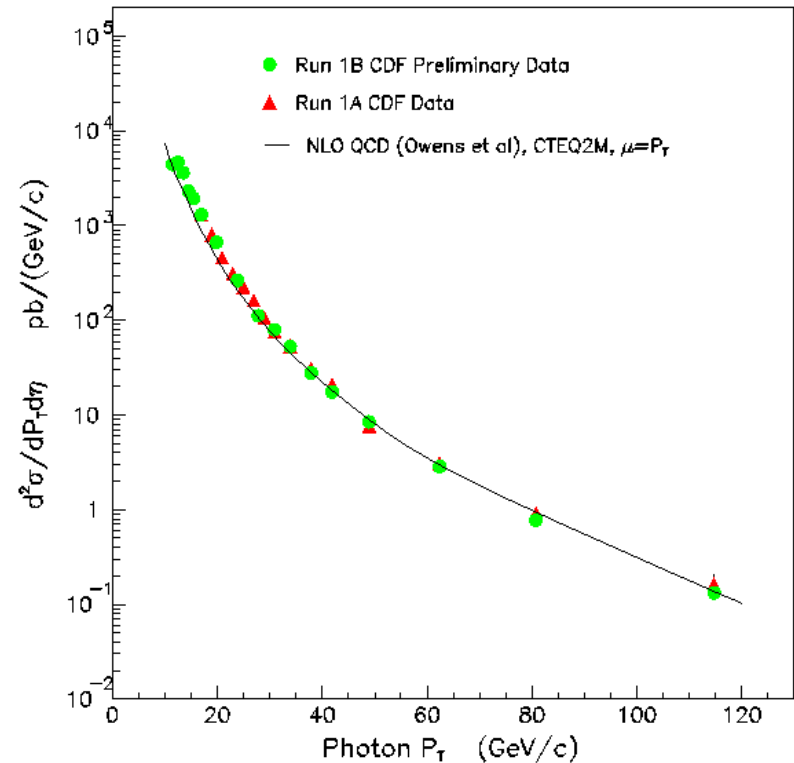
Photon cross sections at the Tevatron



- DØ PRL 84 (2000) 2786



- CDF PRD 65 (2002) 112003



QCD prediction is NLO Owens et al.

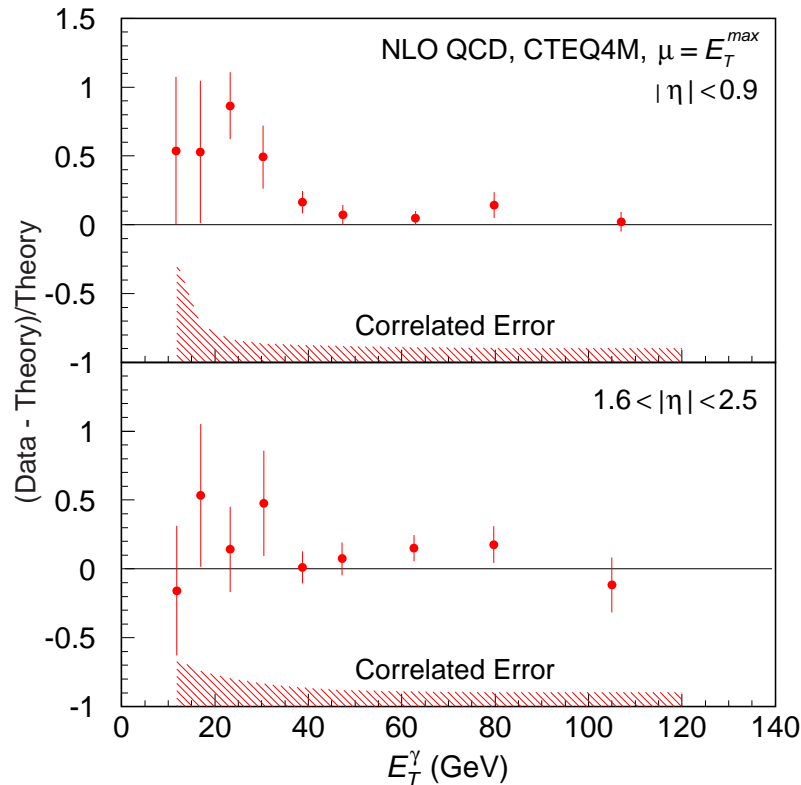
Note: E_T range probed with photons is lower than with jets



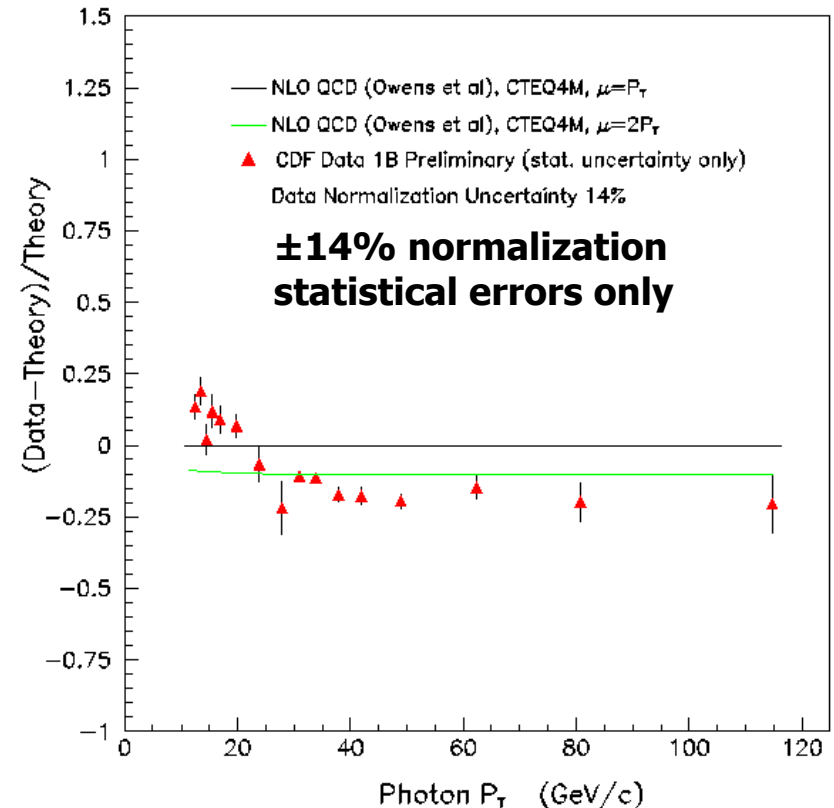
Photon cross sections at the Tevatron



- DØ PRL 84 (2000) 2786



- CDF PRD 65 (2002) 112003



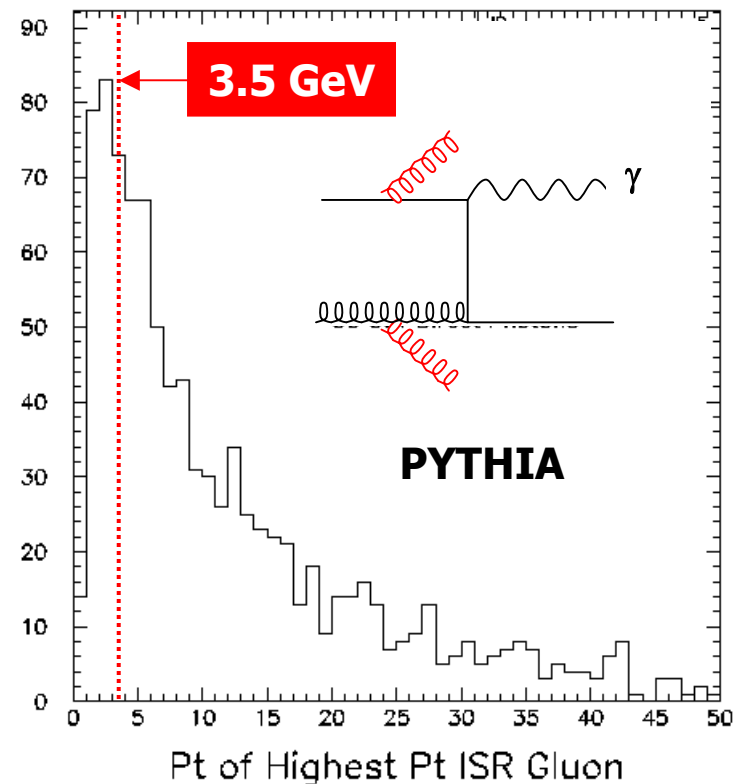
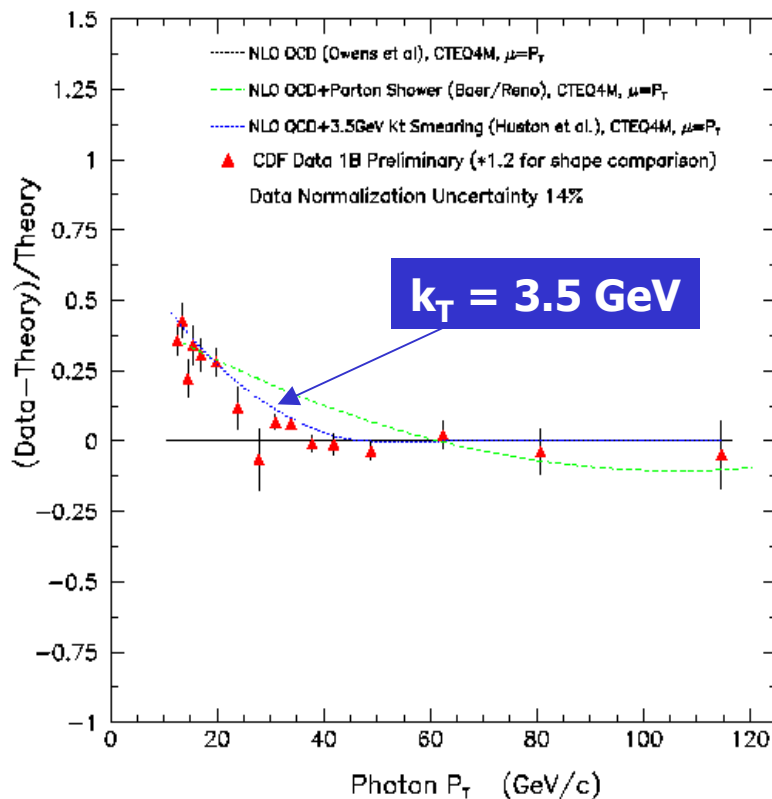
QCD prediction is NLO by Owens et al.



What's happening at low E_T ?

- Gaussian smearing of the transverse momenta by a few GeV can model the rise of cross section at low E_T (hep-ph/9808467)

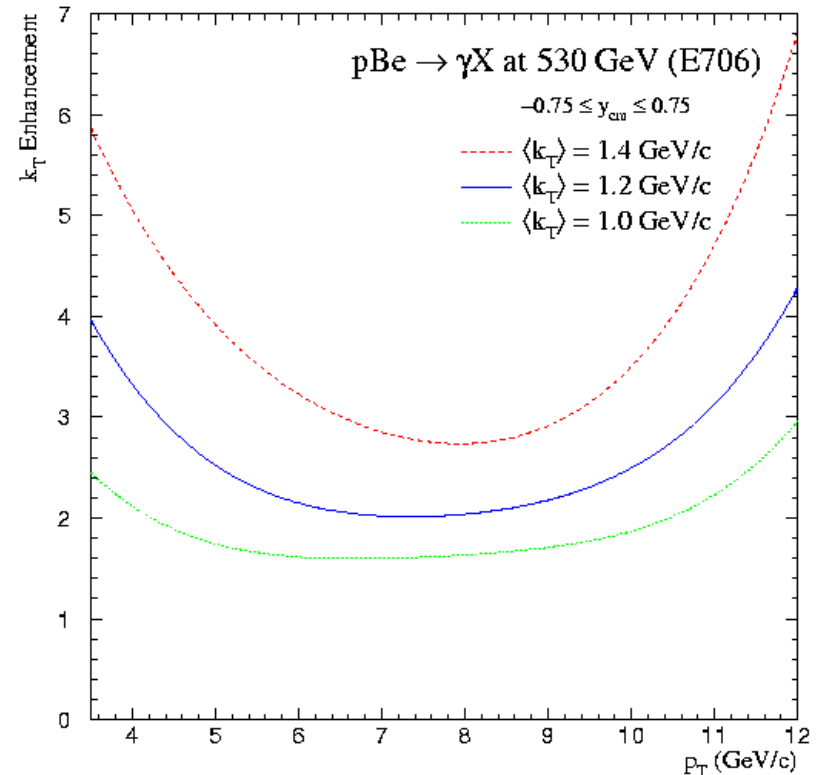
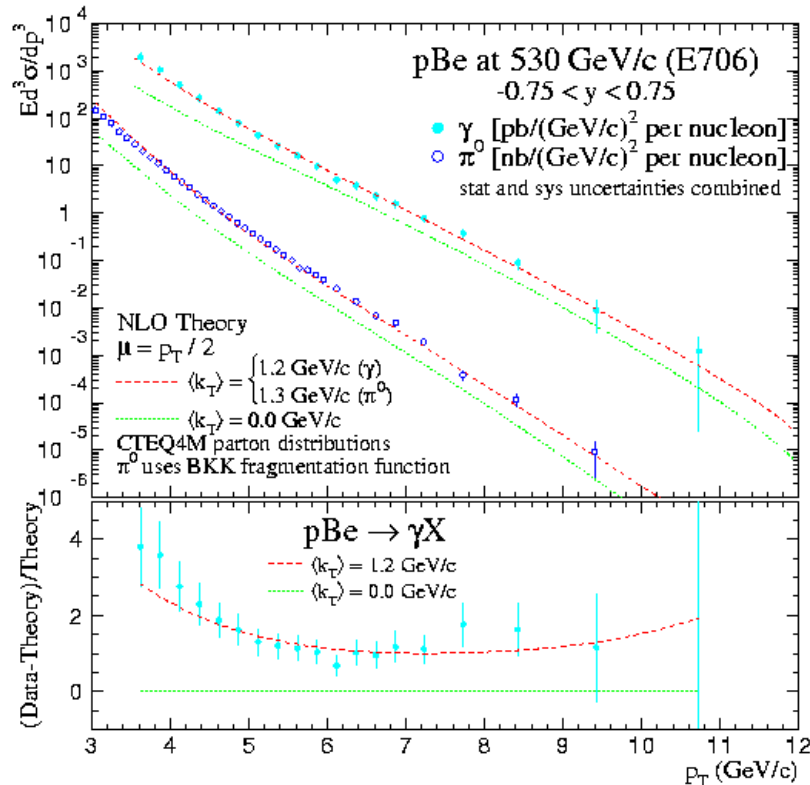
" k_T " from soft gluon emission





Fixed target photon production

- Even larger deviations from QCD observed in fixed target (E706)



- again, Gaussian smearing (~ 1.2 GeV here) can account for the data

Contrary viewpoint

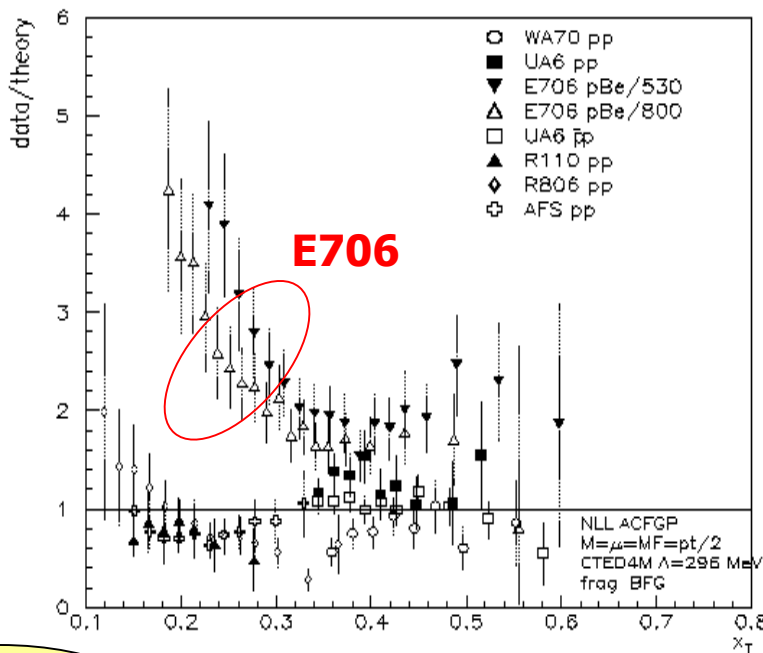
- Aurenche et al., hep-ph/9811382:
NLO QCD (sans k_T) can fit all the
data with the sole exception of E706

“It does not appear very instructive
to hide this problem by introducing
an extra parameter fitted to the
data at each energy”

Ouch!



Aurenche et al.
vs.
E706

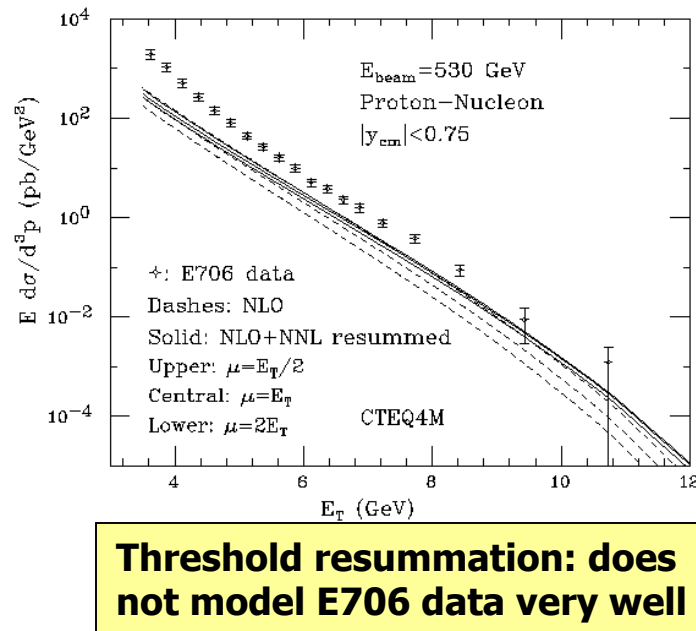




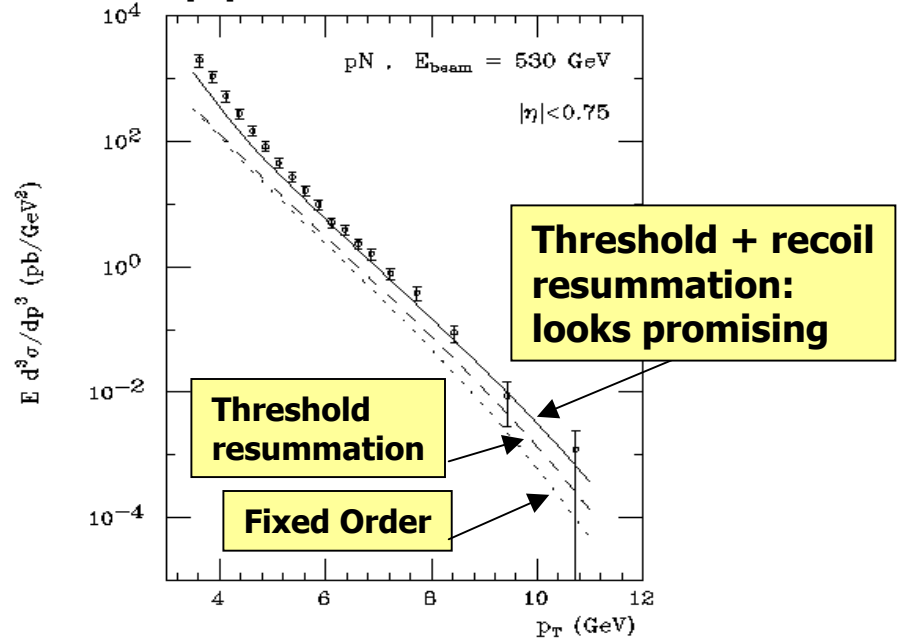
Resummation

- Predictive power of Gaussian smearing is small
 - e.g. what happens at LHC? At forward rapidities?
- The “right way” to do this should be resummation of soft gluons
 - as we have seen, this works nicely for W/Z p_T

Catani et al. hep-ph/9903436



Laenen, Sterman, Vogelsang, hep-ph/0002078



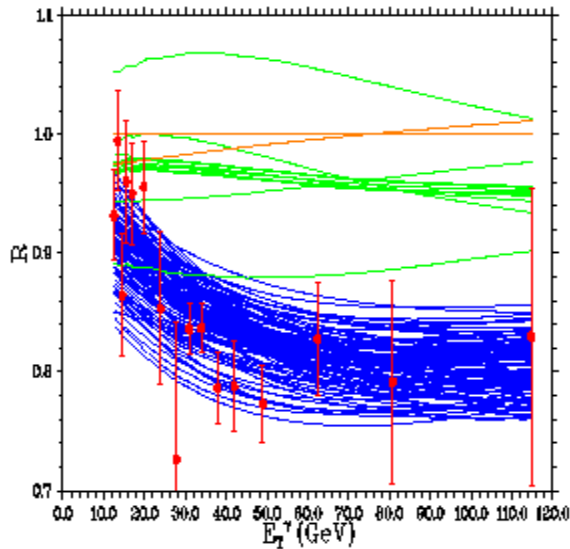


New

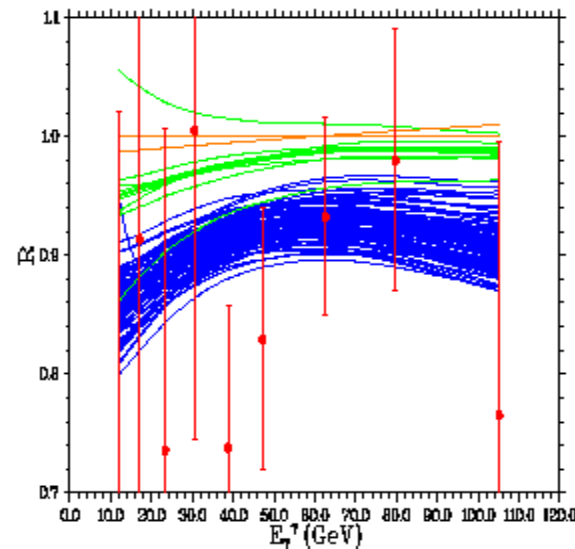
Is it just the PDF?



- New PDF's from Walter Giele can describe the observed photon cross section at the Tevatron without any k_T :



CDF (central)

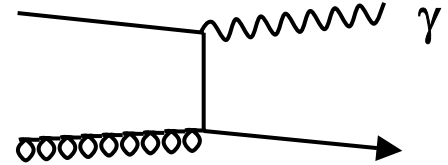


D0 (forward)

Blue = Giele/Keller set
Green = MRS99 set
Orange = CTEQ5M and L



Photons: final remarks

- For many years it was hoped that direct photon production could be used to pin down the gluon distribution through the dominant process:
- 
- Theorist's viewpoint (Giele):
 - "... discrepancies between data and theory for a wide range of experiments have cast a dark spell on this once promising cross section ... now drowning in a swamp of non-perturbative fixes"
 - Experimenter's viewpoint: it is an interesting puzzle
 - k_T remains a controversial topic
 - experiments may not all be consistent
 - resummation has proved disappointing so far (though the latest results look better)
 - new results only increase the mystery
 - is it all just the PDF's?

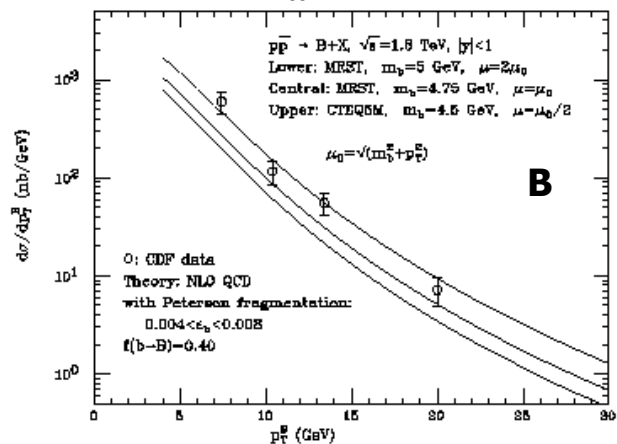
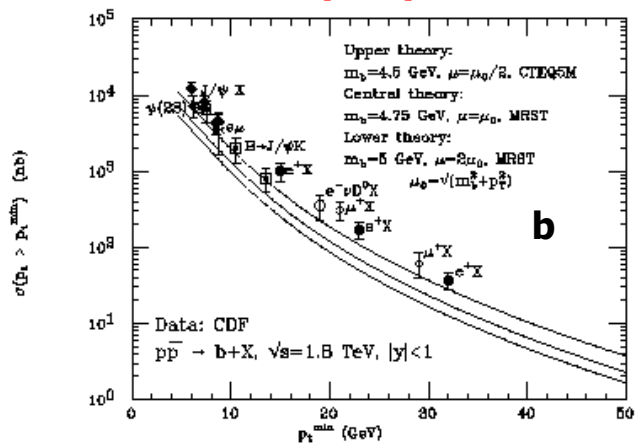


Heavy Flavour Production

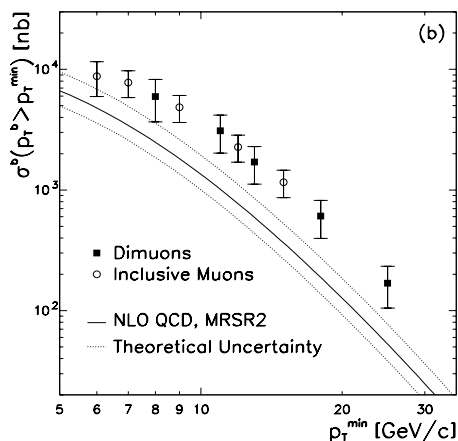


b production at the Tevatron

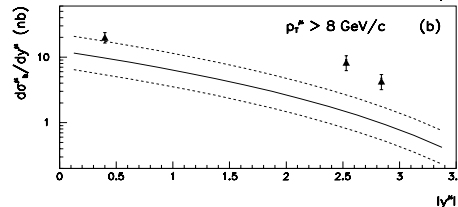
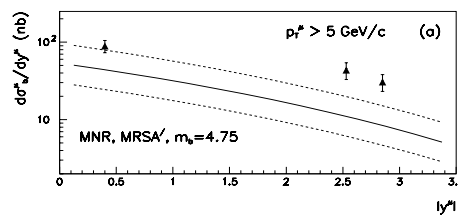
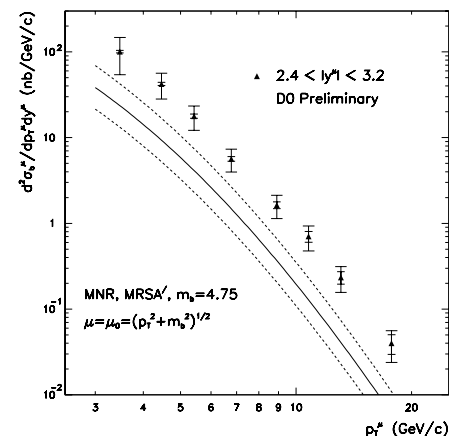
- b cross section at CDF and at DØ



central



forward



Cross section vs. $|y|$
 $p_T > 5$ GeV/c

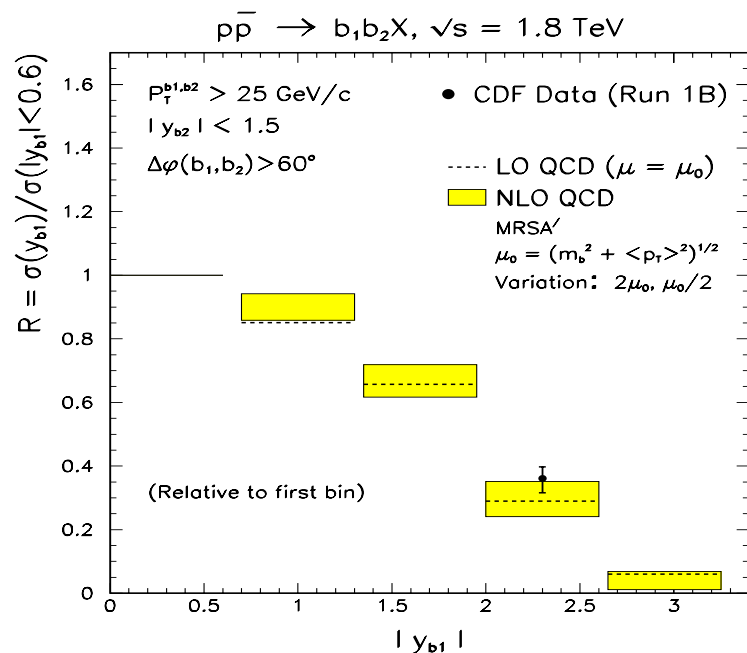
$p_T > 8$ GeV/c

- Data continue to lie $\sim 2 \times$ central band of theory

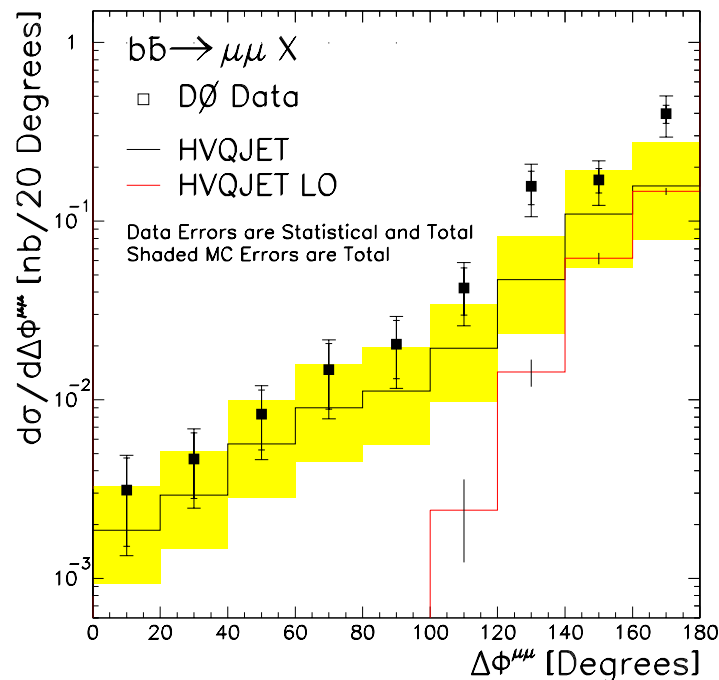


$b\bar{b}$ correlations

- CDF rapidity correlations**



- DØ angular correlations**

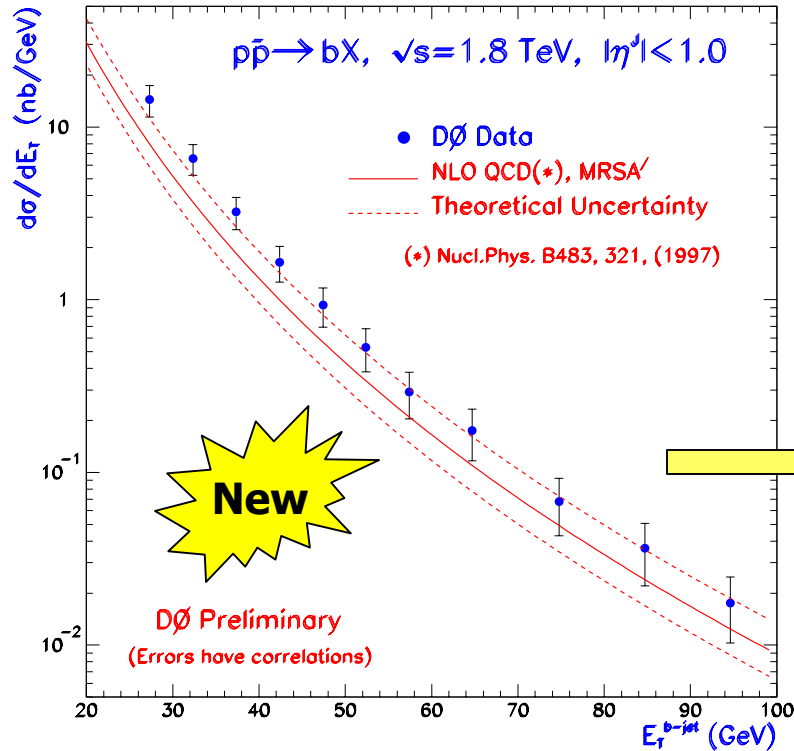


- NLO QCD does a good job of predicting the shapes of inclusive distributions and correlations, hence it's unlikely that any exotic new production mechanism is responsible for the higher than expected cross section**

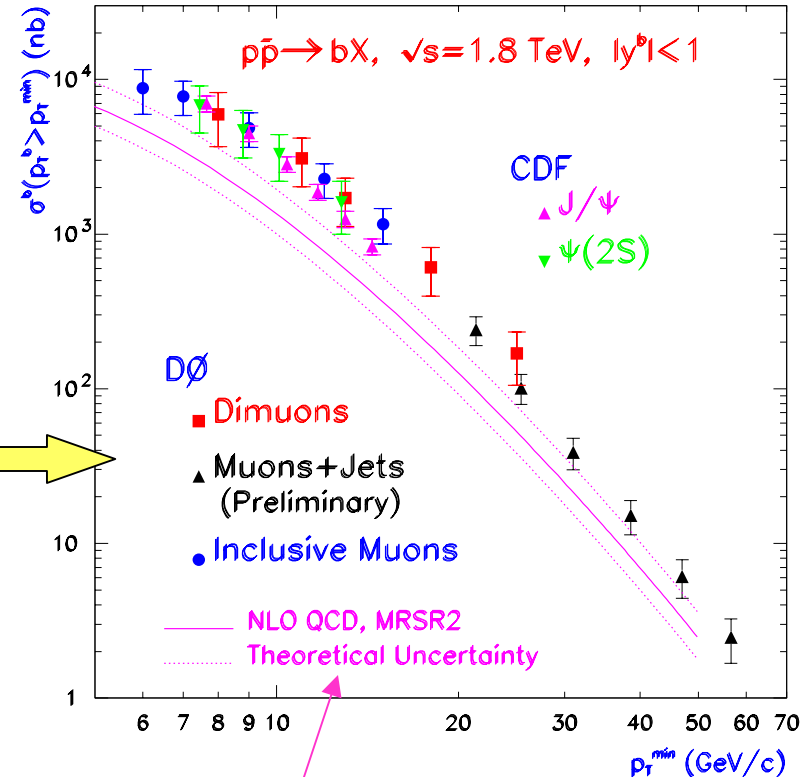


DØ b-jet cross section at higher p_T

Differential cross section



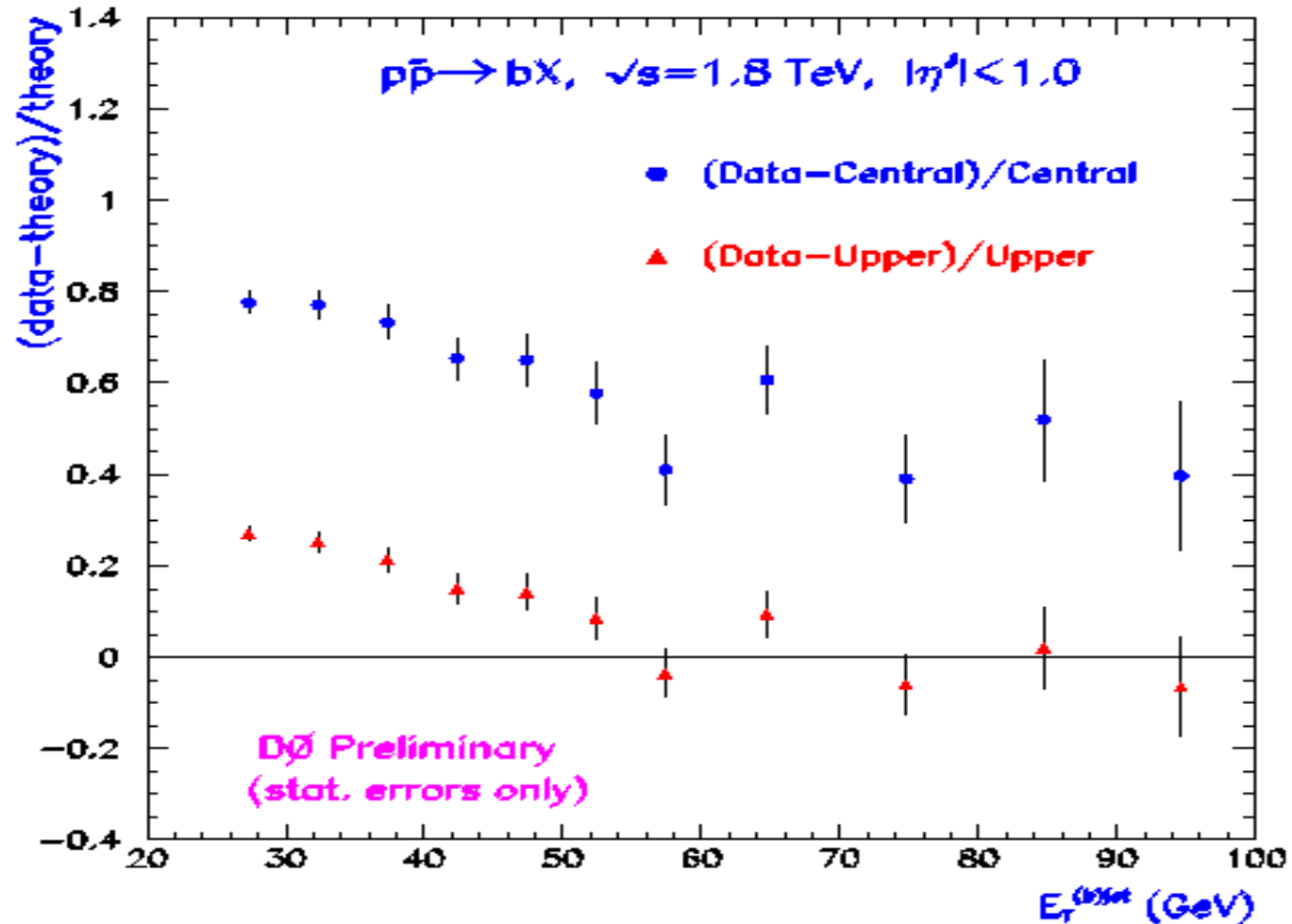
Integrated $p_T > p_{Tmin}$



from varying the scale from $2\mu_0$ to $\mu_0/2$, where $\mu_0 = (p_T^2 + m_b^2)^{1/2}$

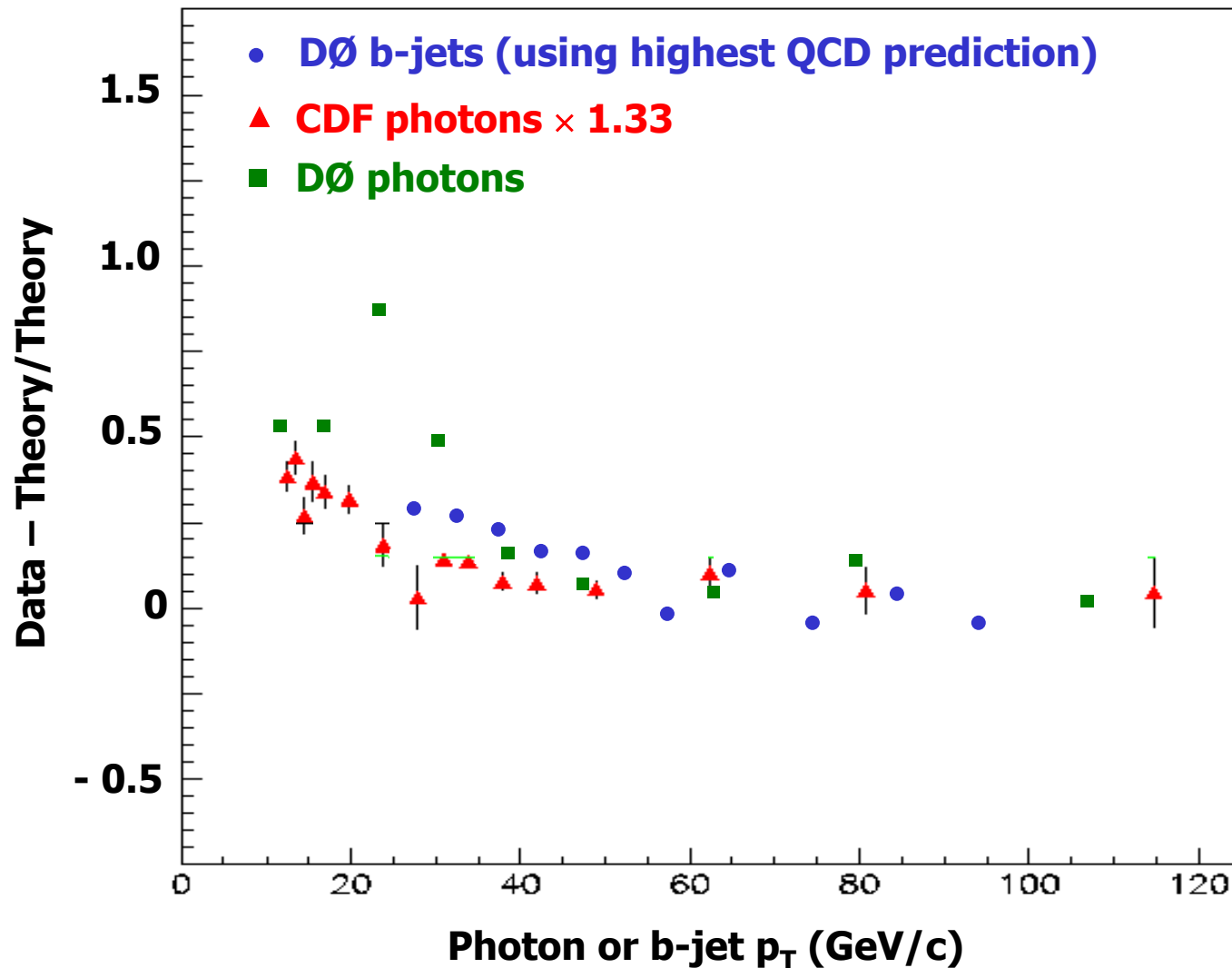


Data – Theory/Theory





b-jet and photon production compared





b production summary

- Experimental measurements at Tevatron, HERA and LEP2 ($\gamma\gamma$) are all consistent and are all several times higher than the QCD prediction
 - factor of ~ 2 at low rapidity
 - factor of ~ 4 at high rapidity
- Modifications to theory improve but do not fix
- New measurement at higher p_T : jets from DØ
 - better agreement above about 50 GeV
 - shape of data–theory/theory is similar to photons
- The same story (whatever that is)?



α_s



New α_s from LEP 1 + SLD data

- LEP EWWG Summer 1999 (G. Quast at EPS99)
 - α_s from $\Gamma_{\text{hadrons}}/\Gamma_{\text{leptons}}$ at m_Z : $\alpha_s(M_Z) = 0.123 \pm 0.004 \pm 0.003^{+0.003}_{-0.003} (m_H)$
 - α_s from full SM fit: $\alpha_s(M_Z) = 0.119 \pm 0.003$

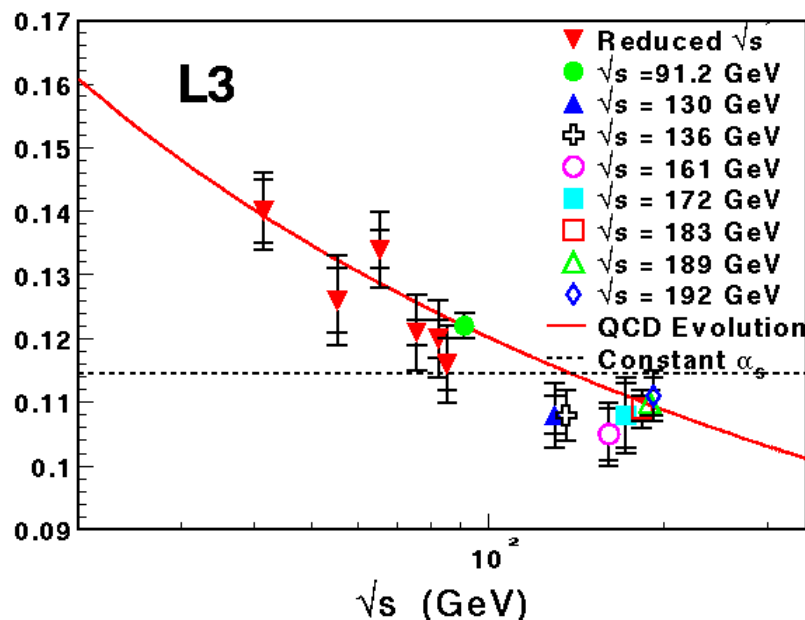
New α_s from DIS data at NNLO

- Santiago and Ynduráin (hep-ph/9904344)
 - extracted α_s from F_2 measured in DIS (SLAC, BCDMS, E665 and HERA)
 - $\alpha_s(M_Z) = 0.1163 \pm 0.0023$
- Kataev, Parente and Sidorov (hep-ph/9905310)
 - extracted α_s from xF_3 measured in CCFR
 - $\alpha_s(M_Z) = 0.118 \pm 0.006$



α_s from LEP 2

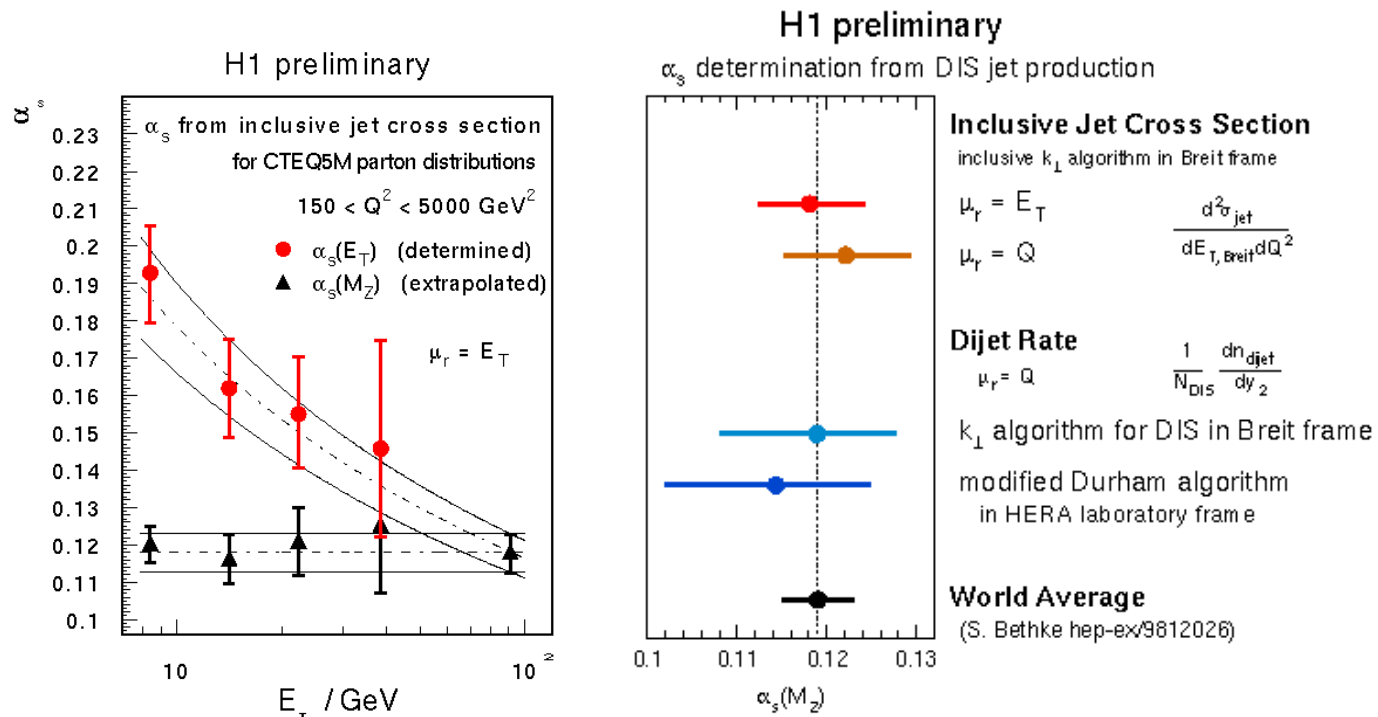
- LEP collaborations have all extracted α_s from event shapes, charged particle and jet multiplicities at $\sqrt{s} = 130 - 196$ GeV.
- Non-perturbative effects modelled with MC programs
- Typical uncertainties around ± 0.006
- L3 and OPAL have nice demonstrations of the running of α_s
 - L3 using radiative events to access lower \sqrt{s}
 - OPAL in combination with data from JADE





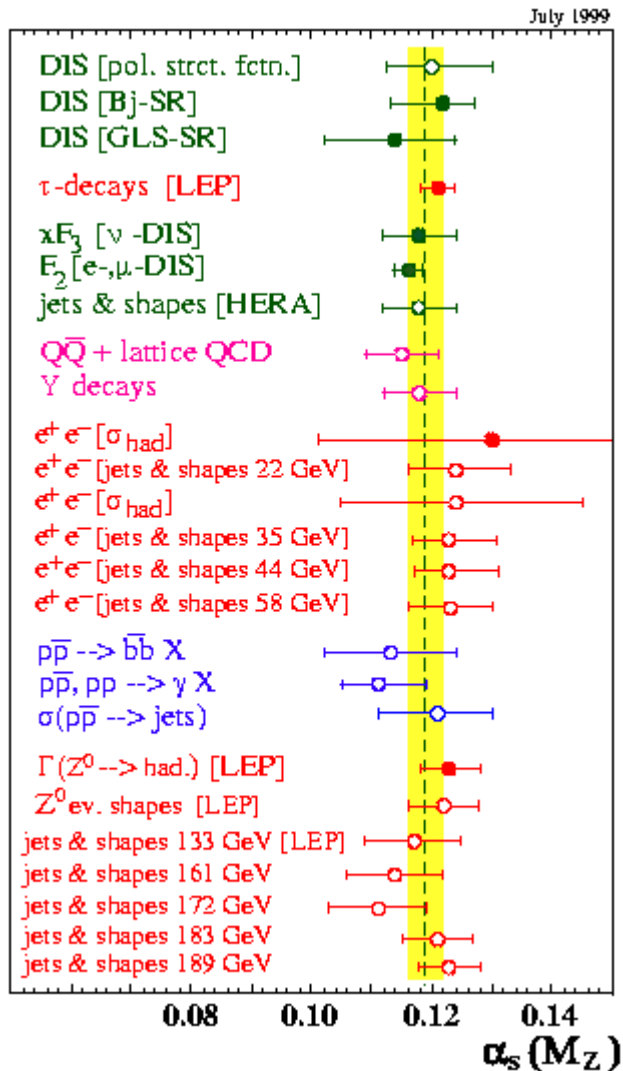
α_s from HERA

- H1 fit the inclusive jet rate $d^2\sigma/dE_T dQ^2$ and the dijet rate
- ZEUS fit the dijet fraction
- Typical uncertainties around ± 0.005 - 0.006





Summer 2002 world average α_s



- From S. Bethke (private communication) average of all 25

$$\alpha_s(M_Z) = 0.117 \pm 0.002$$

- average based only on complete NNLO QCD results (filled circles in plot)

$$\alpha_s(M_Z) = 0.118 \pm 0.003$$

- excellent consistency between low and high energy, DIS, $p\bar{p}$ and e^+e^- , etc.
- Minimal change from previous world average (hep-ex/9812026)
 - $\alpha_s(M_Z) = 0.119 \pm 0.004$ or
 - $\alpha_s(M_Z) = 0.120 \pm 0.005$ excluding lattice



Hard diffraction

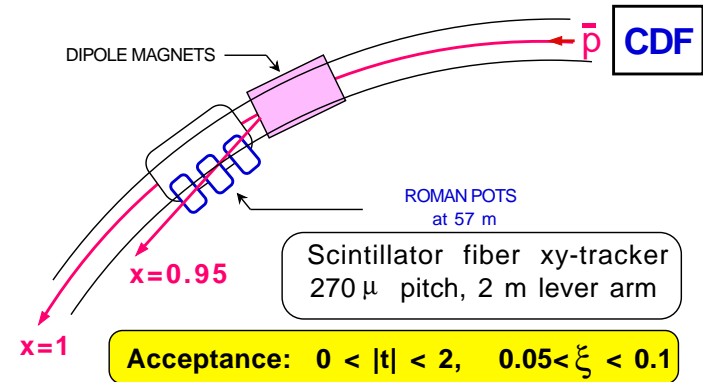


Something we have failed to describe

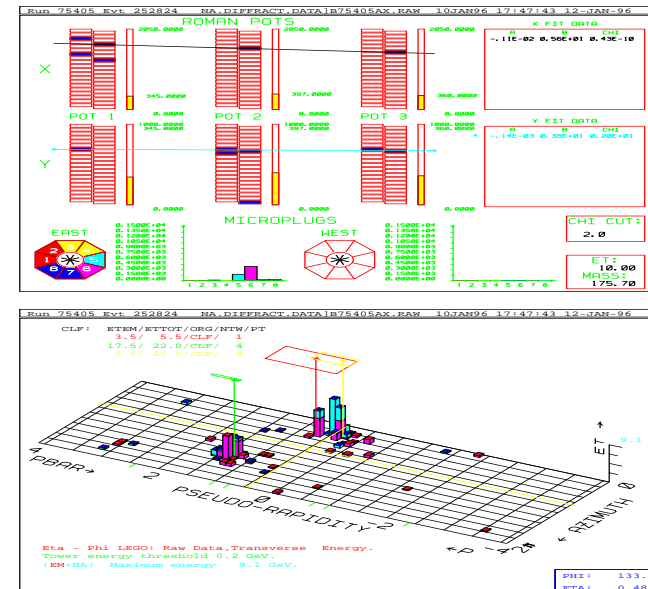


CDF dijet event with Roman Pot track

- Here is dijet production at the Tevatron — a perturbative process, which I have told you is well modelled by NLO QCD
- Except for one detail: in a substantial fraction (a few %?) of these events one of the protons seems not to break up
- Similar observations at HERA



Dijet Event with Roman Pot Track:

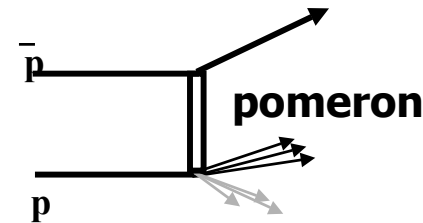
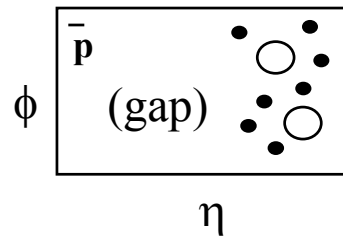




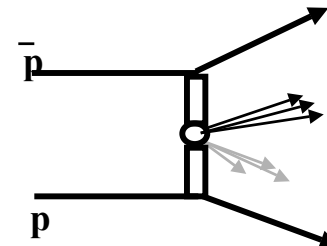
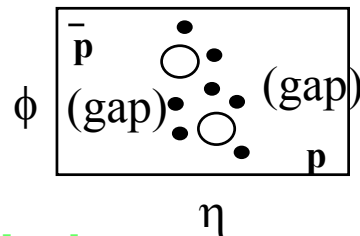
Rapidity Gaps

- Presumed mechanism for such processes is the exchange of a colour-singlet object (a "Pomeron")
- Another consequence of colour-singlet exchange is rapidity gaps (regions of phase space with no particle production)

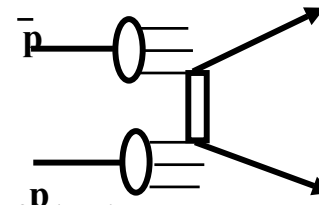
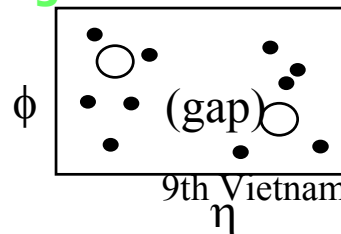
hard single diffraction



hard double pomeron



hard color singlet

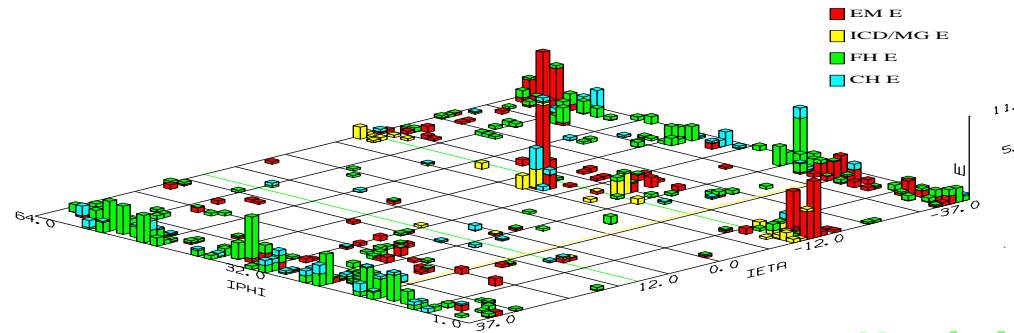




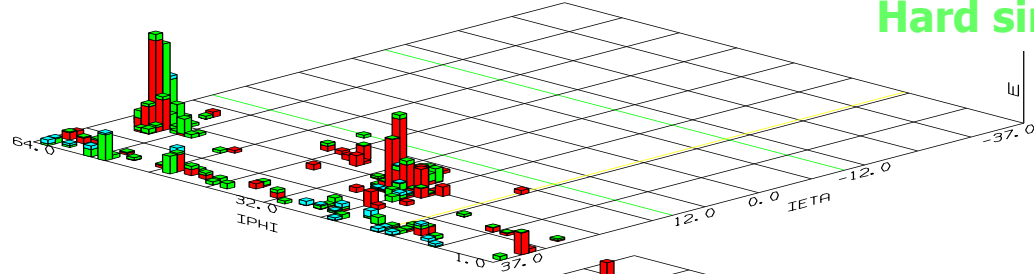
Rapidity Gaps at the Tevatron



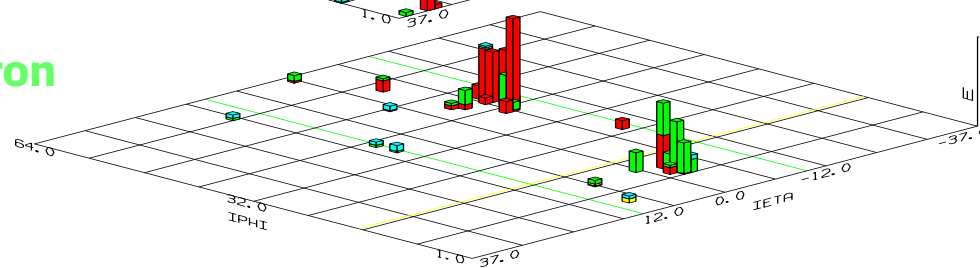
Typical event



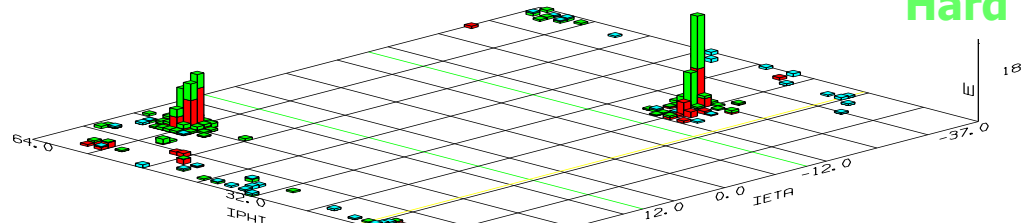
Hard single diffraction



Hard double pomeron



Hard color singlet



Gap events also
seen at HERA

Boaz Klima (Fermilab)

9th Vietnam School of Physics



What does this all mean?

- Attempts to understand in terms of a partonic structure of the pomeron
 - look at jet E_T spectra diffractive vs. non-diffractive
 - look at diffractive fraction at 630 GeV vs. 1800 GeV
 - diffractive W production: quarks in initial state
- Hard to get any kind of consistent picture
- In my view, we need
 - better data (CDF and DØ both plan upgraded Roman Pot systems)
 - a different worldview
 - the picture of an exchanged bound state may not be correct
- It is surely worth pursuing this physics: by beginning with hard, jet production processes which we have some hope of understanding, we can learn about the mechanisms of elastic scattering and the total cross section
 - for example, view diffractive W production not as an unusual kind of diffraction, but as an unusual kind of W production



Some final remarks on QCD



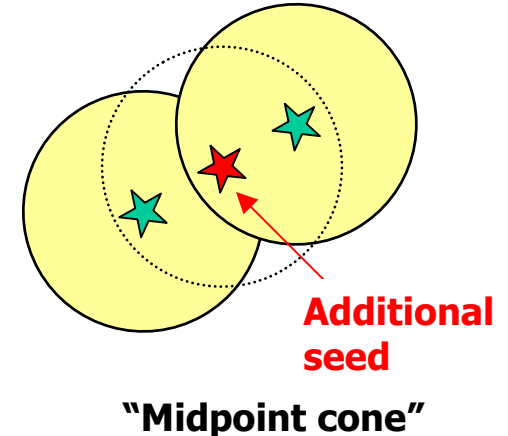
Things we can look forward to

- More data — the next decade belongs to the hadron colliders
- Improved calculations
- PDF's with uncertainties, or at least a technique for the propagation of PDF uncertainties as implemented by Giele, Keller, and Kosower
 - so we won't get excited unnecessarily by things like the high E_T jet "excess"
 - but imposes significant work on the experiments
 - understand and publish all the errors and their correlations
- Better jet algorithms
 - CDF and DØ accord for Run II
 - k_T will be used from the start



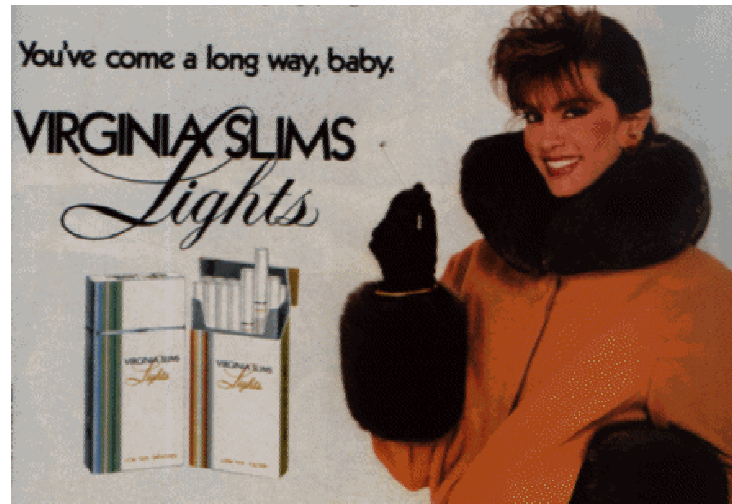
Future Jet Algorithms

- Fermilab Run II QCD workshop 1999:
CDF-DØ-theory
- Experimental desires
 - sensitivity to noise, pileup, negative energies
- Theoretical desires
 - “infrared safety is not a joke!”
 - avoid ad hoc parameters like R_{sep}
- Can the cone algorithm be made acceptable?
 - e.g. by modification of seed choices
 - or with a seedless algorithm?
- Many variations of k_T exist — choose one and fully define it





We've come a long way



- “I can remember when all it took to do QCD was the Born term plus bullshit”
 - sign in Jeff Owens’ office
- “Twenty or even fifteen years ago, this activity was called ‘testing QCD.’ Such is the success of the theory that we now speak instead of ‘calculating QCD backgrounds’ for the investigation of more speculative phenomena...”
 - Frank Wilczek, *Physics Today*, August 2000



Conclusions

We are no longer testing QCD — nowadays calculating within QCD

- **Our calculational tools are working well, especially at moderate to high scales**
 - **the state of the art is NNLO calculations, NLL resummations**
- **Some interesting things (challenges!) are happening as we approach scales of order 5 GeV**
 - **problems calculating b cross sections**
 - **problems with low p_T direct photon production (k_T ?)**
 - **indications of few GeV jet energy effects?**
- **Other challenges for the future**
 - **identification of appropriate jet algorithms**
 - **underlying event in hadron-hadron collisions**
 - **understanding parton distribution uncertainties**
 - **consistent understanding of hard diffractive processes**